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16. Abstract

This document reports the findings of a study which involved the following:

(1) a review and analysis of the existing CTA railcar maintenance program, including the parts supply system, and an examination of alternative railcar rehabilitation programs and their ability to achieve a desired level of reliability; (2) an examination of recent railcar maintenance and rehabilitation/overhaul experiences at other transit authorities and their effects upon car reliability; (3) the identification and quantification of the procedures needed to ensure reliable railcar operation and the recommendation of a maintenance and rehabilitation plan; (4) an evaluation of the present manpower and facilities of CTA in view of the requirements for implementing long-term maintenance plans; and (5) an analysis of CTA fleet reliability and maintainability to establish the cost effectiveness of rehabilitation and replacement program alternatives.

The report underscores the need for more comprehensive data for evaluating maintenance investment decisions. The use of railcar reliability and maintainability data and the cost model development illustrated in this report represents a unique application of such an analytical procedure for an operating transit authority.

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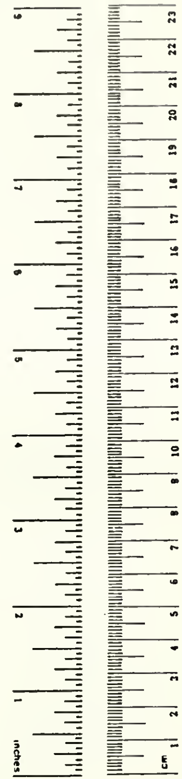
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

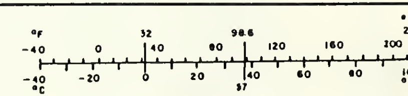
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



RAPID TRANSIT CAR MAINTENANCE
AND OVERHAUL ANALYSIS

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Washington, D.C.

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1.0 INTRODUCTION

The Chicago Transit Authority (CTA) Rapid Transit System operates 1,198 self-propelled transit railcars in 10 fleets over 6 lines. The cars seat approximately 50 passengers and can carry a crush load of 150 passengers. The railcars on all but the Skokie Line (5-50 Series) operate as married pairs in trains of up to 8 cars.

The railcars range in age from 33 years to newly delivered. A fleet of 600 new cars is being delivered which will enable the retirement of all cars that are 25 or more years old. Moreover, a rehabilitation program for 45 railcars that are 24 years old is under way, but no scheduled rehabilitation/overhaul program has been conducted by CTA in over ten years.

A decline in vehicle availability and increasing unscheduled maintenance and time to repair has led CTA engineers to seek assistance in identifying specific maintenance improvement suggestions based upon the current operating and maintenance experience. More specifically, CTA requested Lea, Elliott, McGean & Company (LEM) to examine current CTA maintenance practices and abilities and to compare them with other alternative railcar equipment programs to determine which is most cost effective.

The scope of work involved the following questions related to railcar reliability and maintenance strategies:

1. Can a unit exchange program like the one performed at CTA provide a reliable fleet in view of existing CTA facilities and manpower levels?

2. What extent of rehabilitation is needed to restore/retain the reliability of each series of railcars and at what intervals?

3. For each individual series of railcars, is it more cost effective to rehabilitate the railcars or to replace them?

4. Is it more cost effective to perform railcar rehabilitation in-house or by outside contractor?

LEM carried out a series of tasks aimed at providing the answers to these questions; in addition, LEM identified additional questions and data needs that were examined during the course of the project. Briefly, the five activities which LEM carried out can be summarized as follows:

1. A review and analysis of the existing CTA railcar maintenance program, including the parts supply system, and an examination of alternative railcar rehabilitation programs and their ability to achieve a desired level of reliability.

2. An examination of recent railcar maintenance and rehabilitation/ overhaul experiences at other transit authorities and their effects upon car reliability.

3. The identification and quantification of the procedures needed to ensure reliable railcar operation and the recommendation of a maintenance and rehabilitation plan.

4. An evaluation of the present manpower and facilities of CTA in view of the requirements for implementing long-term maintenance plans.

5. An analysis of CTA fleet reliability and maintainability to establish the cost effectiveness of rehabilitation and replacement program alternatives.

This report is organized as follows: Section 2.0 presents the basic findings and recommendations of the study effort. Section 3.0 focuses on railcar maintenance and overhaul requirements, the experience at CTA and at a number of transit authorities, and the current potential for Federal support of maintenance and overhaul. Section 4.0 presents an examination and evaluation of the CTA railcar performance based upon available CTA data. Section 5.0 discusses a procedure for estimating potential economic benefits that can be derived from improvements in CTA railcar reliability and maintainability, and examines the benefits which this procedure projects. Section 6.0 briefly examines the issues of CTA manpower and facilities with regard to proposed changes in CTA maintenance and overhaul programs.

2.0 FINDINGS AND RECOMMENDATIONS

2.1 INTRODUCTION

The basic objective of this project was "to examine present CTA maintenance practices and abilities and compare them and their results to alternate programs that include rehabilitation or replacement". This objective was met by carrying out the five major activities described in Section 1.0. This section summarizes the findings and recommendations which have resulted from the conduct of these activities.

2.2 FINDINGS

- o Transit authority experience indicates that railcar maintenance requirements can vary due to equipment, the operating environment, the operating schedule, etc., but the lack of proper maintenance always leads to more rapid deterioration of equipment, increased failures in service, higher maintenance costs, and higher life cycle costs.

- o CTA is currently maintaining its railcars on virtually a failure maintenance basis; the one component of preventive maintenance at the present time is a 6,000-mile inspection.

- o Although there have been series-wide repair and replacement campaigns and some subsystem rebuilding due to excessive equipment failures, CTA has not carried out any interim heavy maintenance or overhaul programs on any of the existing fleet.

- o A total rebuilding of the 2000-Series railcars has been estimated to be too costly by CTA engineers and anything less would not be effective; a rebuilding project for the 2200-Series railcars, although costly, is necessary if they are to reach their design life.

- o In view of the documented experience at transit authorities in the U.S. and the status of CTA equipment, a program of heavy maintenance and

overhaul is reasonable and a necessity if the railcar equipment is to reach its design life. More detailed inspection of individual railcars will provide a basis for more accurate estimates of overhaul requirements.

- The funds needed to improve the condition of CTA's railcar fleet and to reinstate an effective and thorough preventive maintenance program must be primarily borne by CTA or other local or state funding sources; UMTA takes the position that the overhaul of railcar equipment is a routine maintenance activity, not supported by Federal funds. UMTA will, however, provide support for upgrading railcar components. Thus, any major overhaul campaign at CTA must examine the potential for equipment upgrade. However, administration insistence upon reduced Federal support to transit may further jeopardize this support in the future.

- CTA data for reliability and maintainability analysis is very limited; when the new Maintenance Management Information System (MMIS) is implemented throughout the system it should provide a basis for analyses and evaluations of the preventive maintenance efforts. Routine monitoring and analyses of equipment performance of the type conducted in this project will require additional procedural and methodological development.

- An in-house railcar overhaul program at the level needed is not immediately possible with existing CTA staff and facilities. CTA and other transit authorities have successfully contracted for railcar overhauls and if an overhaul program at the level needed is initiated at CTA then contract overhaul is the only viable option.

- The data analyses showed that reliability expressed by mean time between failures was highest for the new 2600-Series and lowest for the 15-year old 2200-Series (2200-Series MTBF of 52 car-hours perfailure; 2400-Series MTBF of 58 car-hours per failure; 2600-Series MTBF of 78 car-hours per failure). Fleet availability showed a similar result (80 percent for 2200-Series, 86 percent for 2400-Series, 89 percent for 2600-Series).

- With regard to individual railcar subsystems, the three worst offenders for the three-car series studies are the same, though with different rankings. These subsystems, doors/communications, propulsion, brakes, were also found to be major offenders in the UMTA Transit Reliability Information Program (TRIP) study.

- The analyses indicate that improvements in railcar maintainability and availability at CTA can yield potential cost savings due to an overall reduction in maintenance costs and fleet requirements.

- Improvements in railcar maintainability and availability can be achieved in two major ways, changes in maintenance practices and changes in subsystem component design. Expansion of CTA's preventive maintenance program to include the 5-year heavy maintenance effort and the 10-year car overhaul and/or subsystem retrofit or upgrade should yield railcar performance improvements.

- A unit exchange program by itself has not been shown to be an effective method of preventive maintenance at CTA or elsewhere. Unit exchange can be integrated as part of a comprehensive preventive maintenance program.

- A decision regarding rebuild vs. buy-new involves a number of factors, including design life of the equipment, equipment condition, suitability of the equipment for rebuild, the time value of money and the availability of funds. Since CTA has decided not to rebuild the 2000-Series because of the condition of the equipment and the cost of the needed work and since the 2200-Series is but 15 years old this aspect is not a major factor in the near future.

2.3 RECOMMENDATIONS

- In view of the continuing deterioration of the railcar equipment, current CTA maintenance practices, and transit experience CTA should add 5-year and 10-year overhaul elements to its current preventive maintenance program.

3.0 RAILCAR MAINTENANCE AND OVERHAUL

3.1 BASIC MAINTENANCE CONSIDERATIONS

This section describes some of the basic concepts of maintenance which have application in railcar maintenance. In following sections we briefly examine maintenance programs and experiences at CTA and a number of other transit authorities. Finally, we investigate the implications of this information on CTA maintenance programs and plans.

The activities of a railcar maintenance department include both the scheduled maintenance work that is performed on railcar equipment to avoid failures in revenue service and the corrective maintenance work that is performed after failures have occurred. In general, maintenance activities are designed to accomplish the following objectives:

1. To ensure the safety and reliability of the equipment.

2. To restore safety and reliability to their design levels when deterioration has occurred.

3. To obtain the information necessary for equipment design improvement of items whose actual reliability proves inadequate.

4. To accomplish the above at a minimum total cost, including maintenance costs and the costs of residual failures.

Preventive maintenance consists of the tasks necessary to retain an item (railcar) in a specified condition through systematic inspection, detection and prevention of incipient failure. The complete collection of these tasks, together with their assigned intervals, is referred to as the scheduled maintenance program. In this report maintenance actions, including inspections, consist of cleaning, lubricating, adjusting equipment, repairing failed or worn components, and replacing short-lived components in order to restore the equipment to adequate standards of performance.

A portion of equipment failures that occur during revenue service and are detected require immediate attention in the form of unscheduled maintenance so that equipment can continue in service. Other failures may go undetected or may be corrected at the end of the run or at the end of the day. Major equipment failures can render the equipment inoperable and require that the equipment be somehow removed to a maintenance shop for corrective work. Finally, the need for a corrective maintenance task may be identified during a scheduled maintenance activity which is unrelated to that activity but which necessitates additional maintenance activity. Nonetheless, this corrective maintenance action may avoid a failure in service.

In addition, proper railcar maintenance may involve other activities related to keeping the equipment in reliable working order. Overhauls are activities in which major subsystems are removed and substantially rebuilt or replaced with new equipment designed to original specifications. It is likely that several overhauls will be performed during a car's life as part of the preventive maintenance program. Railcar rebuilding usually entails stripping the railcars to the bare frame and replacement of all subsystems with rebuilt or new equipment designed to original specifications. In an upgrade original equipment is replaced with modern improved equipment. The actual work is coordinated to achieve a consistent life expectancy for the equipment.

In general, maintenance and overhauls are necessary to enable the railcars to achieve their design life. A rebuild helps to extend the useful life of the railcar and improve equipment reliability, availability, and maintainability. It may also improve compatibility with other, newer equipment, improve ride quality, improve passenger comfort and convenience, and reduce energy consumption.

In recent years certain maintenance approaches have received new labels and have been promoted as alternative solutions to traditional railcar maintenance approaches. One such label is "progressive maintenance" under which all components of a car are replaced with overhauled units on a progressive basis with the car being shopped only for short periods. Another is termed "responsive maintenance"; in it items are repaired or replaced upon critical analysis. In fact, these approaches are not new (even though the names may be) and continue to be used in the rail transit industry.

For example, a form of progressive maintenance is practiced actively by GO TRANSIT of the Toronto Area Transit Operating Agency of Ontario, operator of the commuter rail system in that area. GO TRANSIT uses diesel electric railroad locomotives together with lightweight push-pull coaches with head-end electric power and cab-cars at the non-locomotive end. The coaches are very simple, with air-conditioning/heating ventilating systems using 575 vac/3 phase power, and conventional railroad airbrake equipment. The system has a severe peak, light base and weekend traffic typical of most railroad commuter services. As a result, nearly all cars are assigned on weekdays and are not available for long-term (i.e., more than a few hours) maintenance. Therefore, GO TRANSIT developed a progressive maintenance plan in which replacement of subsystems with reconditioned equipment is done on weekends. The air-brake equipment is especially addressed, generally at 2- and 4-year mandated intervals. The HVAC system is treated similarly. During the week, maintenance man-hours are devoted to component overhaul. This approach works well for trucks and equipment that can be readily removed and replaced. It can be used for light overhauls provided that carborne wiring does not need to be replaced, or that the car body does not need to be repaired.

Responsive maintenance is not a totally new concept either. Spin-testing of car trucks during inspections, which was pioneered by CTA and has been practiced there for many years, is an example of effective responsive maintenance as part of preventive maintenance. The truck spin-test includes listening to: (1) journal bearings, (2) traction motor bearings on both ends, and (3) gear-unit bearings, each of the three shafts (6 bearings). A bearing that is beginning to fail can be detected by an experienced mechanic listening with an amplifier and earphones. This concept was adopted by PATCO in 1974 and is used rigorously there as well. Since its adoption, PATCO has had only a few -- perhaps four -- bearing failures in service. PATCO operates about 4 million car miles per year, so has operated about 40 million car miles with 4 failures, or 10 million car miles between failure. No bearing failures have occurred within the past five years -- since the 1968 SKF cylindrical bearings were replaced. None of the Timken bearings used since 1977 have failed in service.

This is an important application of responsive maintenance; it assures that incipient failures will be detected and the offending part replaced, and at the same

time, it allows maximum utilization of the service component on a time or mileage basis, which may discard some of its service life. This is especially prevalent if a rigid replacement on a time basis is used because certain cars may accumulate mileage slowly compared to the fleet average.

The value of having a scheduled maintenance program with consistent and proper performance of all required preventive maintenance is that it helps accomplish the following:

1. Reduction of road failures to some acceptable minimum; road failures are extremely counterproductive because they:

   - inconvenience passengers riding on and waiting for the affected train and following trains.
   - require the diversion of personnel resources to diagnose the problem and implement a remedy.
   - may require the removal of a train from revenue service.
   - may require the assistance of another train to move the crippled or dead train off line.

2. Reduction in equipment life cycle costs.
3. More efficient use of available resources.
4. Stabilization of the workforce at the car repair facilities.
5. Reduction in resources required to perform unscheduled maintenance which is the principle reason for overtime expenditures.
6. Improvements in revenue fleet dependability (schedule adherence) and maintains user satisfaction.
7. Optimization of equipment overhaul work requirements and scheduling.

The lack of a proper scheduled maintenance program usually reflects a lack of funds and the resultant practice of deferred maintenance. Deferred maintenance is often accepted as a short-term solution to maintenance budget reductions but nearly as often becomes institutionalized with the consequences being increasingly rapid deterioration of the railcar equipment, increasing road failures, increasing customer dissatisfaction, and increasing car life cycle cost.

3.2 CURRENT CTA MAINTENANCE PROGRAM

The railcar maintenance requirements at CTA are closely tied to the railcar equipment currently in use; CTA railcar equipment is summarized in Exhibit 3-1. Railcars are assigned to the six lines according to a schedule such as that shown in Exhibit 3-2. The Skokie Swift Line is the only line with a single series of dedicated equipment. The other lines utilize a mix of equipment.

The CTA maintenance program has evolved over a number of years from a well-recognized, well-structured program of maintenance and overhauls to a program based on a unit exchange system and finally to the current program which relies essentially upon a 6,000-mile inspection effort. The 6,000-mile inspection is the primary preventive maintenance activity currently undertaken by the CTA.

The 6,000-mile inspection sequence was initially used on the CTA 6000 Series railcars; it was based on PCC car maintenance practice and is a conservative approach. It was quite reasonable for the 6000-Series since the cars were basically an adaptation of the PCC cars.

CTA initiated a unit exchange program in the early 1970s to replace components and parts at a pre-determined life point in order to prevent some of the failures in service which were occurring on an increasing basis; the unit exchange program was also intended to reduce (or even eliminate) the need for scheduled overhauls which had been sharply curtailed due to budget cuts. The basic concept of unit exchange was borrowed from a CTA bus program which had proven fairly successful. Budget reductions at the time prevented the implementation of an overhaul program.

The unit exchange program focussed on major subsystems such as propulsion equipment, trucks, and axles; it neglected everything from the floor up. At that time UMTA funds were used to remanufacture the equipment that was being changed out. Maintenance crews on the 2nd (3 p.m.-11 p.m.) and 3rd (11 p.m.-7 a.m.) shifts performed the changeouts. Eventually, however, this program was eliminated due to further budget reductions which severely reduced 2nd and 3rd shift maintenance staff and due to a plan to create a new total overhaul

EXHIBIT 3-1

CTA RAILCAR FLEET

CAR SERIES	YEARS DELIVERED	CAR BUILDER	NO.	NOTES
6000*	1950-1959	St. Louis	350	Converted PCC cars.
5-50	1959-1960	St. Louis	45	Converted PCC cars; seven are Skokie Line cars; all can operate singly.
2000	1964	Pullman-Standard	176	
2200	1969-1970	Budd	144	
2400	1977-1978	Boeing	194	
2600	1981-**	Budd	354	Current purchase

* Number in fleet is decreasing as 2600-Series railcars are delivered.
** Current contract for delivery of 600 cars; 354 as per 4/18/85.

EXHIBIT 3-2

RAILCAR ASSIGNMENT EFFECTIVE MID-MARCH 1984

OP-x84057
March 9, 1984

CAR SERIES	WEST-NORTHWEST	WEST-SOUTH	NORTH-SOUTH	RAVENSWOOD	EVANSTON	SKOKIE SWIFT	TOTAL
2001-2180 (PULLMAN) YEAR(S) DELIVERED: 1964		2003-2024 (22) (22)	2001-2002 (2) 2025-2042 (18) 2046-2126 (64) 2121-2180 (60) (164)				176
2201-2352 (BUDD) YEAR(S) DELIVERED: 1969-70	2201-2288 (88) 2291-2308 (16) 2309-2314 (6) 2317-2340 (24) 2343-2352 (10) (144)						144
2401-2600 (BOEING) YEAR(S) DELIVERED: 1977-78		2401-2448 (46) 2449-2480 (32) 2463-2516 (34) 2519-2578 (60) (172)	2579-2600 (22) (22)				194
2601-3200# (BUDD) YEAR(S) DELIVERED: 1981-	2713-2850 (136) (138)	2601-2872 (72) (72)		2673-2712 (40) (40)			250
5-50 (ST. LOUIS) YEAR(S) DELIVERED: 1959					5-22 (18) 27-28 (2) 31-38 (8) 40-41 (2) 43-48,50 (7) (37)	23-26 (4) 30 (1) 39,42 (2) (7)	44
51-54 (ST. LOUIS/PULLMAN) YEAR(S) DELIVERED: 1947-48						51-54 (4) (4)	4
6001-6720 (ST. LOUIS) YEAR(S) DELIVERED 6001-6200 1950-51 6201-6470 1954-55 6471-6670 1956-56 6671-6720 1959	6513-6514 (2) 6523-6524 (2) 6527-6532 (6) 6535-6536 (2) 6641-6644 (4) 6547-6546 (2) 6553-6560 (8) 6563-6574 (12) 6577-6582 (6) 6585-6586 (2) 6589-6590 (2) 6597-6602 (6) 6605-6610 (6) 6613-6614 (2) 6619-6620 (2) 6625-6634 (10) 6637-6648 (12) 6651-6666 (16) (102)		6165-6166 (2) 6373-6374 (2) 6175-6176 (2) 6377-6378 (2) 6163-6184 (2) 6389-6394 (6) 6191-6196 (6) 6423-6424 (2) 6201-6202 (2) 6427-6430 (4) 6205-6206 (2) 6439-6440 (2) 6215-6216 (2) 6451-6452 (2) 6219-6220 (2) 6459-6460 (2) 6251-6254 (4) 6475-6476 (2) 6265-6266 (2) 6483-6486 (6) 6269-6270 (2) 6491-6492 (2) 6275-6284 (10) 6495-6500 (6) 6291-6292 (2) 6509-6510 (2) 6299-6300 (2) 6667-6670 (4) 6307-6308 (2) 6673-6678 (6) 6317-6320 (4) 6681-6688 (8) 6331-6334 (4) 6731-6738•(6) 6343-6352 (10) 6741-6742•(2) 6357-6360 (4) 6771-6782•(12) 6363-6364 (2) 6785-6788•(4) 6369-6370 (2) (154)	6069-6076 (8) 6079-6088 (8) 6089-6110 (22) 8113-8118 (6) 6121-6122 (2) 6125-6126 (2) 6131-6142 (12) 6145-6154 (10) 6157-6158 (2) 6161-8164 (4) (76)	6015-6016 (2) 6053-6058 (6) 6061-6062 (2) 6065-6068 (4) 6689-6692 (4) 6695-6720 (26) (44)		376
REQUIRED FOR SERVICE	280	216	224	96A	66A	5	667
SCHEDULED MAINTENANCE	10	8	10	2	2	1	33
SUBTOTAL	290	224	234	98	68	6	920
UNASSIGNED RESERVE EQUIPMENT	94	42	96	18	13	5	266
TOTAL ASSIGNED	384	266	330	118	61	11	1168

EFFECTIVE MID-MARCH 1984

MKC.src

program which was not implemented. Consequently the CTA maintenance program became a failure maintenance effort with the 6,000-mile inspection as the sole scheduled maintenance activity.

The unit exchange program was based on the development of life expectancies for individual components. Some data still exists from a later Planned Maintenance Program, conducted in 1978. Component life cycles (see Exhibit 3-3) were based upon combinations of shop, terminal and unit exchange reports; only shop records were used to determine life cycle estimates for traction motors, axle assemblies, trucks, and control groups. Past experience with the equipment was also considered in forming the basis for the life cycle estimates. Transportation records were used to establish standard mileage figures for each car series, e.g., 6000-Series — 42,000 miles per year; 2000-Series — 42,000 miles per year; 2200-Series — 69,000 miles per year. Unfortunately, the Planned Maintenance Program did not effect major changes in the preventive maintenance program which remained essentially a 6,000-mile inspection effort.

Available data at CTA to gauge the success of its maintenance program is limited (as discussed in greater detail in Section 4.2). However, information on car availability supplied by CTA engineers illustrates the effects of past years of deferred maintenance on CTA car equipment. The following data presents the changing car availability situation from 1966 to 1984:

CTA CAR AVAILABILITY HISTORY

Year	Fleet Size	Schedule Requirement	Percent Availability
1966	1142	987	86.4
1970	1239	1007	81.2
1971	1181	975	82.5
1984	1200	887	73.9

If 1984 availability was equal to 1966 availability, then the fleet size requirement in 1984 would have been only 1,027 cars as opposed to 1,200 cars. At current replacement costs (about $850,000 per car), the difference represents an investment of about $147 million.

EXHIBIT 3-3

EXAMPLE CTA COMPONENT LIFE CYCLES

1.	Current Collector Shoe; 6000 Series - Flipper Type	78,918 miles
2.	Current Collector Shoe; 2200 Series - Flipper Type	64,446 miles
3.	Current Collector Shoe; 2000/6000 Series - Gravity Type	66,990 miles
4.	Rockwell Truck; Cars 2001-2180	450,000 miles*
5.	Pioneer III Truck; Cars 2201-2350	430,884 miles
6.	17KG192 Control Groups	546,000 miles*
7.	Car Body Paint; Cars 2001-2180	168,000 miles
8.	Batteries, B6H; 6000 Series	210,000 miles*
9.	B-3 Truck Axle Assembly	252,000 miles*
10.	B-2 Truck Axle Assembly	252,000 miles*
11.	GA-47 Gear Box; Series 2000/2200	777,000 miles*
12.	1250 Traction Motor; Cars 2001-2180	350,000 miles
13.	Air Comfort Air Filter; 2200 Series	18,000 miles
14.	Drive Shaft; Cars 2001-2180	231,000 miles
	Cars 2201-2350	345,000 miles
	Cars 6001-6720	357,000 miles
15.	Converter; 2000/2200 Series	9 years*
16.	Inverter; 2000 Series	9 years*
17.	Pilot Motors; Cars 6001-6720, 5-54	100,000 miles

SOURCE: CTA Planned Maintenance Program

* CTA Estimate

In our investigation we also examined the manufacturers' maintenance manuals which are a prime source of information for establishing maintenance intervals and a maintenance plan and schedule. These manuals usually provide the information which the transit authority needs to know in order to carry out maintenance on the equipment. The manuals are normally provided as part of the equipment purchase contract. (However, this has not always been the case.)

It is recognized that the manufacturer tends to be conservative in recommending maintenance intervals and the operator usually takes the suggested intervals as guidelines. The transit authority is well-advised to follow the manufacturer's intervals during the warranty period, simply in view of protecting its warranty claims. Beyond the warranty period, the CTA should write its own procedures taking account of the manufacturer's suggested intervals, its instructions for maintenance procedures, and the CTA's own experience. Service bulletins and maintenance manuals for current CTA fleet components should be updated and completed as appropriate.

One reason that deviations from the manufacturer's intervals will be necessary is that specific maintenance intervals are made by system and subsystem suppliers, not the carbuilder. As a result, the intervals are not always related to each other or fit into a reasonable standard maintenance period. For example, a 6,000-mile inspection interval for contact tips is not compatible with a 7,000-mile inspection interval for traction motor brushes.

CTA is in the process of instituting a computerized maintenance management information system (MMIS) for the rail system; the rail MMIS is based upon the bus MMIS which has proven to be a successful management tool. The rail MMIS was undergoing initial installation in two rail maintenance terminals and debugging and tests were under way while this study was being carried out. The MMIS data on rail maintenance actions can provide a useful basis for future analyses of equipment reliability, maintainability, and availability but was not sufficient for this study.

3.3 CTA PROPOSALS FOR MAINTENANCE AND OVERHAULS

3.3.1 CTA Car Rehabilitation Proposal

The CTA Engineering Department, recognizing the need to improve the condition of the existing fleet and, therefore, the need to supplement the current 6,000-mile inspection as the sole preventive maintenance activity, prepared a proposal for a railcar equipment rehabilitation program in 1983. This program would be conducted on a 10-year cycle during which all car systems would be removed and reworked to bring them up to new-car standards; the car body and car interior appointments would be completely inspected and repaired or replaced as needed. The proposal called for components with a life less than 10 years or which benefit from an intermediate maintenance cycle to be scheduled for rehabilitation under a new planned maintenance program. In addition, unit exchange of larger systems or components would be utilized as necessary for unscheduled maintenance actions.

The proposed rehab program was designed to accommodate about 100 cars per year to keep the fleet in good condition. It suggested using a dedicated facility with a rehab staff, recognizing that current facilities and staff are not available and that an outside contractor would be preferable. The proposal was not adopted in its entirety but some projects have been initiated. The following paragraphs provide a summary of the proposal adjusted to take account of current rehab projects:

1. 5-50-Series: These cars are similar to the 6000 Series cars (which are being replaced with the new purchase of 2600 Series cars) except that they can run as singles and nine are configured so they can run both 3rd rail and catenary. They are PCC car conversions and are in fair physical condition. They are currently being overhauled by Morrison-Knudsen at a cost of $188,000 per car for the first 30 and $176,000 per car for the remainder. The first cars to be completed were returned to Chicago by April, 1985.

2. 6000-Series: At the present time CTA is carrying out a rehab of about 20 cars of this series at Skokie Shop. A major portion of this effort is body work. Current plans do not call for additional rehabs.

3. 2000-Series: A rehab of the 2000 Series railcars is no longer being considered by CTA. These cars have been a serious maintenance problem since they were delivered. In 1983 CTA estimated the cost of rehab and upgrade of these cars at $755,000 per car. At current new car costs this cannot be considered as cost effective. An alternative (as stated in 1983) is to reduce the use of the cars by using them (1) as peak period trippers and (2) on routes where service demand would be reduced.

4. 2200-Series: These railcars were delivered in 1969-1970 so they are all about 15 years old, an appropriate age for a mid-life overhaul. They have not undergone an overhaul as yet, but major repairs (component overhauls) have been made to the cars. For example the propulsion system has been repaired, the air conditioning equipment has been repaired many times as needed, brake calipers have been rebuilt several times, and the steel-aluminum wheels are being changed-out for all-steel wheels as they wear out. On the other hand, items which need an overhaul include the couplers, traction motors, brakes, train control system, and doors.

5. 2400-Series: These cars have been in service since 1976-1977 and have high mileage; a 5-year heavy maintenance program for them was cancelled so that by 1986-1987 these cars will be due for a 10-year overhaul.

6. 2600-Series: These cars will begin reaching 10 years of operation by 1990 and should receive a 10-year overhaul then.

In addition to the proposals for car rehabs, CTA has suggested a car purchase program which would follow the current 2600-Series purchase. At the time of this study no funding action has been taken for either of the program plans.

3.3.2 CTA Maintenance Program Proposal

The CTA Engineering Department has also proposed a rapid transit car maintenance program which consists of four major components: a 6,000-mile inspection, an annual inspection, a 5-year mid-term heavy maintenance, and a 10-year car overhaul/rehab. These are described in more detail below:

1. <u>6,000-Mile Inspection</u>
   Routine maintenance of the equipment in accordance with supplier recommendations and preventive maintenance based on experience.

2. <u>Annual (50,000-Mile) Inspection</u>
   All the equipment suppliers have recommended annual maintenance actions that should be followed to insure reliability and proper operation. These actions go beyond the routine work performed every 6,000 miles and are considered to be preventive maintenance.

3. <u>5-Year (250,000 Mile) Mid-Term Heavy Maintenance</u>
   This component consists of heavy inspection and maintenance on the car and its systems involving some tear-down and intensive check-out and adjustment of all the systems and equipment on the car. This extensive preventive maintenance component will insure the cars operate with maximum reliability until the overhaul/rehab component rebuilds the equipment. The heaviest work consists of the overhaul of the traction motors, brake calipers, and motor couplings and the wheel re-profiling. This would be conducted at Skokie Shops on a production basis to rework 130 cars per year. A more detailed work description is included in Exhibit 3-4. This activity occurs when cars are 5 years old and then between each major overhaul/rehab cycle.

4. <u>10-Year (500,000 Mile) Overhaul/Rehab</u>
   This component consists of tearing down and rebuilding to like-new condition of many car subsystems. This is a full scale overhaul/rehab of the railcar which will insure another 10 years operation with minimal

EXHIBIT 3-4

WORK STATEMENT FOR
5-YEAR MID-TERM MAINTENANCE

- Overhaul traction motors and couplings.
- Overhaul brake calipers.
- Turn wheels.
- Heavy inspection and correction of all defects.

    1. Control groups
    2. M-A set and low voltage system
    3. Door system
    4. Communications
    5. Cab signals
    6. A/C system
    7. Motorman cab clean up and fix up
    8. Opening sash overhaul
    9. Sanders and boxes
    10. Seats
    11. Battery
    12. Couplers and drawbar

- Thorough interior and exterior cleaning and repair of damage

SOURCE: CTA Staff

service failures. This work would be performed by an outside contractor off CTA property. A more detailed work description is included in Exhibit 3-5.

Recognizing that implementation of such a program would constitute a major change in CTA car maintenance practice, the CTA Engineering Department pointed out that the program would be closely associated with the car rehab plans discussed in Section 3.3.1. With the contract rehab of the 5-50 Series (beginning in 1984) and a proposed overhaul/rehab program involving cars 2201-2350 in 1986-87 and cars 2401-2600 in 1988 and the introduction of the 600 new 2600 Series cars through 1987, the work effort needed in the terminals and in Skokie Shops to maintain the fleet would likely decrease. This should free up manhours for an expanded 6000 mile inspection, for the (planned) annual inspections, and for the (planned) 5-year Heavy Maintenance at Skokie Shops. (The 5-year Heavy Maintenance, proposed in the 1984 CTA Budget, has not been approved.)

EXHIBIT 3-5

WORK STATEMENT FOR 10-YEAR OVERHAUL/REHAB

- Rebuild control groups
- Rebuild gear boxes, journal bearings
- Overhaul motors and couplings
- Overhaul brake calipers
- Turn wheels (or replace as needed)
- Overhaul truck frames and replace cables, rubber parts and wear surfaces
- Overhaul air comfort system and controls -- rebuild compressors and perform mechanical rebuilding
- Overhaul light fixtures and sockets
- Overhaul all cab equipment, master controller, control panels, seat, etc.
- Overhaul opening sash
- Overhaul sign system
- Overhaul door operator and electrical system
- Replace any damaged car wiring, conduits, ducts, boxes
- Heavy inspection and correction of all defects and damage

    1. Communications
    2. Cab signals
    3. Seats
    4. Low voltage power supply and battery charger
    5. Car interior and exterior trim and panels

- Overhaul sanders and boxes
- Overhaul end door closers and latches
- Overhaul MA set and controls
- Overhaul battery and box and tray
- Overhaul couplers and drawbars
- Repaint and replace/repair Scotchcal
- Floor work as required

SOURCE: CTA Staff

3.4 MAINTENANCE PROGRAMS AND EXPERIENCE OF OTHER TRANSIT AUTHORITIES

In attempting to evaluate the CTA maintenance program and make recommendations, we examined the maintenance programs and experience of a number of other transit authorities. It was not our intent to conduct a detailed analysis of specific maintenance actions and schedules and translate these to CTA; that level of detail was not appropriate for this study. Moreover, the resolution of factors such as duty cycle, operating environment, noncomparable equipment, etc., was beyond the scope of this study. On the other hand, an examination of the experiences at other transit authorities with maintenance programs, fleet availability, car overhauls and the like is instructive for the current CTA situation. In the following sections the experiences at NYCTA, PATCO, SEPTA, and MBTA as they relate to CTA are reviewed.

3.4.1 NYCTA Maintenance and Overhaul Experience

The situation in New York City as it applies to the New York City Transit Authority (NYCTA) has been well documented.* Political pressures kept fares and government subsidies below the levels needed for anything other than deferred maintenance from the time of the reorganization which created the NYCTA in 1953. During the 1960s many experienced maintenance personnel left the authority; through the 1970s there was a continuous shortfall of monies required to properly maintain the NYCTA fleet. The ultimate consequence was a continued decline in equipment performance in terms of decreased mean distance between failure (MDBF) as illustrated in Exhibit 3-6.

During this period the maintenance program was, in principle, based on an inspection cycle with three levels, A, B, and C; this inspection cycle is still used. The A inspection is performed at 5,000-mile intervals; it is a brief inspection which includes checking fluids, adding battery water, testing batteries and making minor adjustments. At 10,000 miles there is a B inspection which includes everything in

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* See, for example, Newman, Dennis, "Overhaul of Rapid Transit Cars", Presented at APTA Rapid Traisnt Conference, June 22, 1983, Pittsburgh,

EXHIBIT 3-6

MDBF EXPERIENCE AT NYCTA

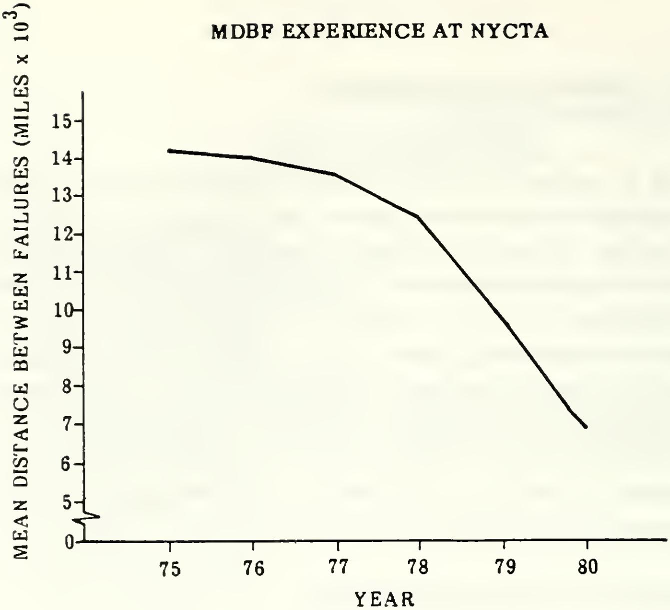
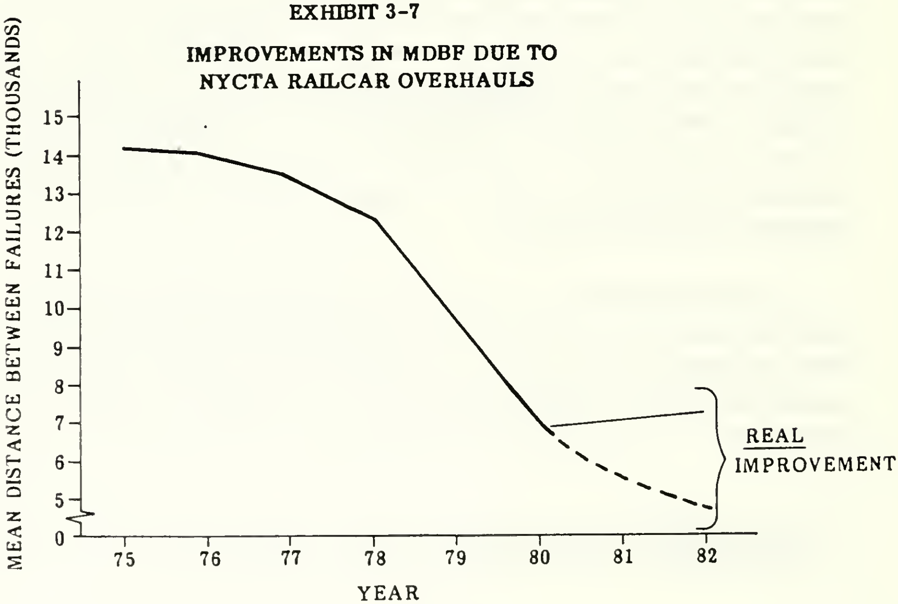


EXHIBIT 3-7

IMPROVEMENTS IN MDBF DUE TO NYCTA RAILCAR OVERHAULS



the A inspection plus inspection and repair of components in electrical, door, air, propulsion, and truck systems; some additional troubleshooting is also performed. The A-B sequence is repeated until 30,000 miles have accumulated whereupon a C inspection is performed; the C inspection includes a B inspection plus additional work on each of the subsystems and a complete car cleaning.

During the 1970s, this inspection cycle, although it enabled the system to continue to operate, did not address some of the major maintenance and overhaul needs of railcar systems. In the early 1980s NYCTA management organized a major funding package, the cornerstone of which is a major fare-backed bonding authority, which provided for a major overhaul program to be integrated with the inspection cycle and as a result the MDBF has been improved. Exhibit 3-7 illustrates NYCTA's representational estimate of improvement; specific quantitative estimates of improvements are not available from the existing NYCTA data base.

With its new maintenance and overhaul budget capability NYCTA embarked on a 5-year capital improvement program designed to rehabilitate and replace its capital assets. The deterioration of the fleet is exhibited by the steady decline in the MDBF (mean distance between failure) from 1975 to 1980 (shown in Exhibit 3-6). This decline was exacerbated by an increase in the average age of the fleet (see Exhibit 3-8).

In addition to the changes in the overall maintenance program NYCTA also began a program of major repairs to vehicle subsystems, specific equipment and subsystem repairs and changeouts for portions of the fleet; the performance of these subsystems was such that basic preventive maintenance actions alone could not improve their performance characteristics. In particular, a set of projects was designed for the R44 fleet. It should be noted that although these cars are only about 10 years old, they have proven to be very maintenance intensive. MDBF values for each of the individual car fleets illustrates the overall difficulties with the R44 cars (see Exhibit 3-9).

The new overhaul program involves a D overhaul at 180,000 miles. It includes rebuilding major subassembiles of the air brake system and the magnet valves and relays of the propulsion system. The E overhaul performed at 360,000 miles is far

EXHIBIT 3-8

AVERAGE AGE OF FLEET AT NYCTA

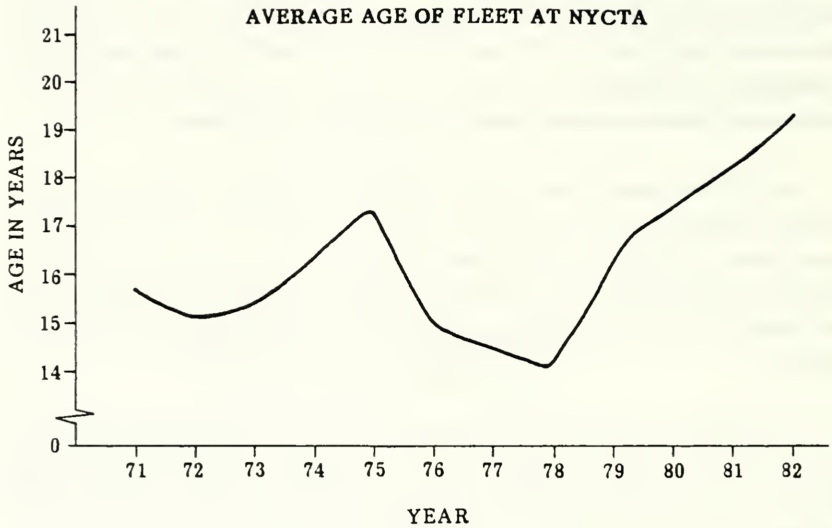


EXHIBIT 3-9a

CAR MDBF FOR IRT (NYCTA)

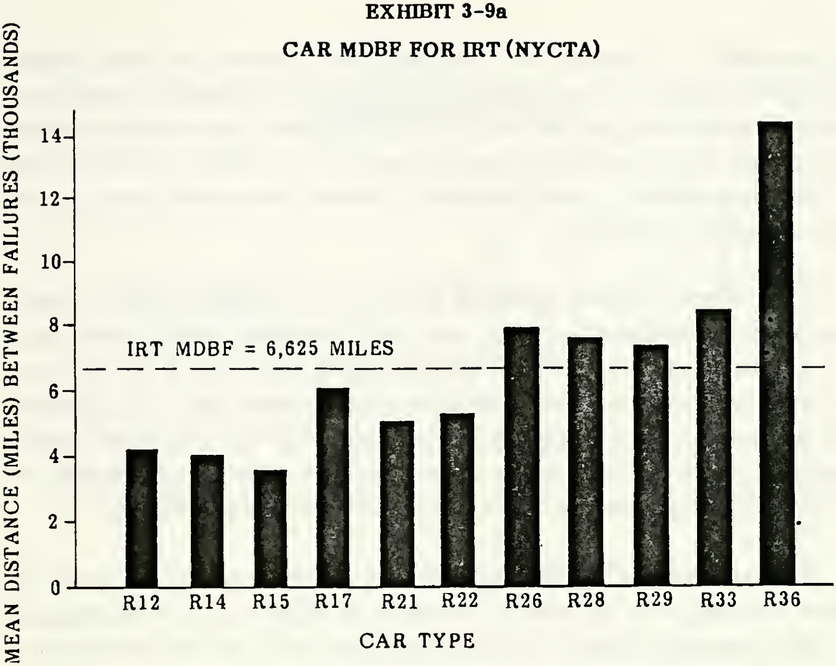
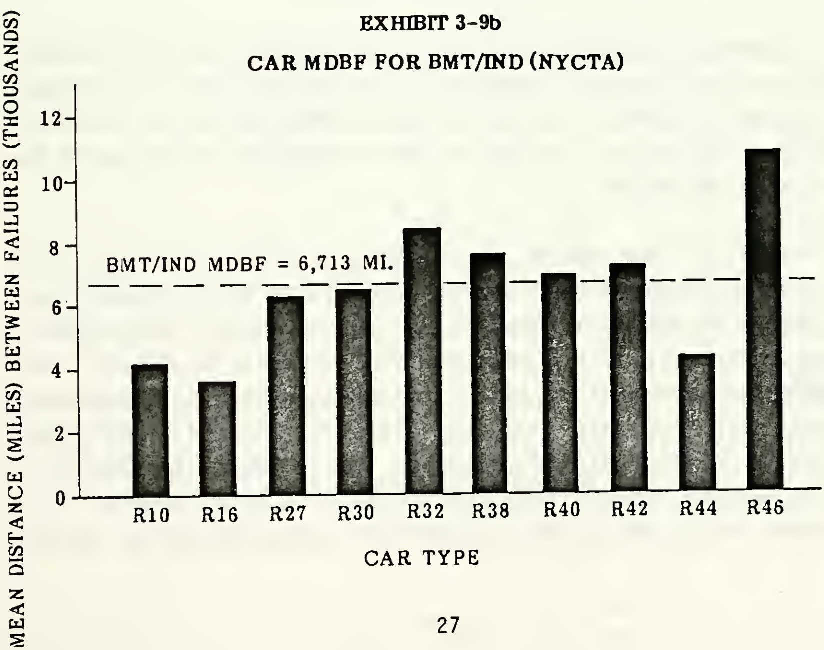


EXHIBIT 3-9b

CAR MDBF FOR BMT/IND (NYCTA)



more extensive. It includes the D overhaul plus rebuilding air brake system assemblies; couplers; compressors; heating and ventilation systems; door relays; door operator brush and spring replacement; lighting; air-operated parts of the car body; all motors; some truck components, such as shoe beam assemblies, shock absorbers and tread brake units; and some propulsion controller components, such as arc chutes, air cylinders, and relays.

The F overhaul includes everything on the E plus rebuilding additional major assemblies of the propulsion controller, such as cam switches, shunts, contact tips, and a complete truck rebuild; it takes place at 720,000 miles. The G overhaul is to take place when the railcar reaches about one-half its design life or at 1,080,000 miles. It includes the F overhaul plus a complete rewiring of the group switch controllers, electric control panels, and replacement of major components such as door operators, motor generator sets, and compressor systems, as necessary.

The ideal schedules for car inspections and for car overhauls are shown in Exhibits 3-10 and 3-11. The state of car equipment at NYCTA at the initiation of the overhaul program, however, was such that all cars except the R44 and R46 cars required a G overhaul as the first overhaul.

Engineering cost estimates were made for each of the overhaul levels so that NYCTA could have a reasonable expectation of the costs involved. The D overhaul was estimated at $5,000 per car; the E overhaul at $60,000 per car; the F overhaul at $85,000 per car; and the G overhaul at about $130,000 for the R36 cars if the work is performed in-house.

Since NYCTA was somewhat space-constrained and maintenance facilities were undergoing rehabilitation simultaneously with the start of car overhaul work, a pilot program was initiated to determine the feasibility and cost effectiveness of utilizing outside contractors to perform the needed overhauls on the R36 cars. Four companies were contracted to overhaul four railcars each. The pilot program yielded a number of benefits to NYCTA including the refinement of the work scope, specification improvements, prequalifications of contractors, identification of potential problems, improved cost estimates, and lower bids. Benefits to the contractors include gains in car, equipment and materials familiarity, logistics

EXHIBIT 3-10
CAR INSPECTION CYCLE

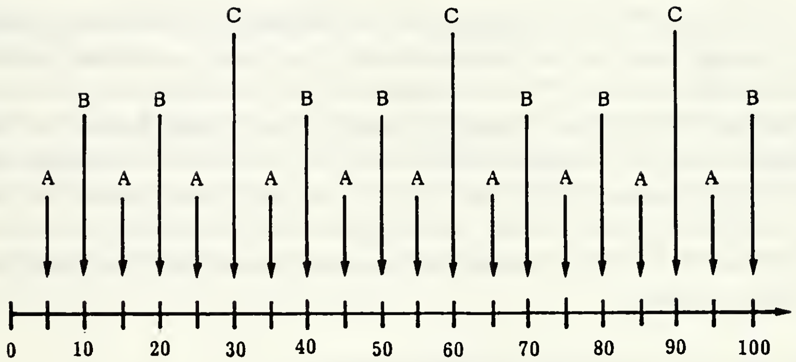
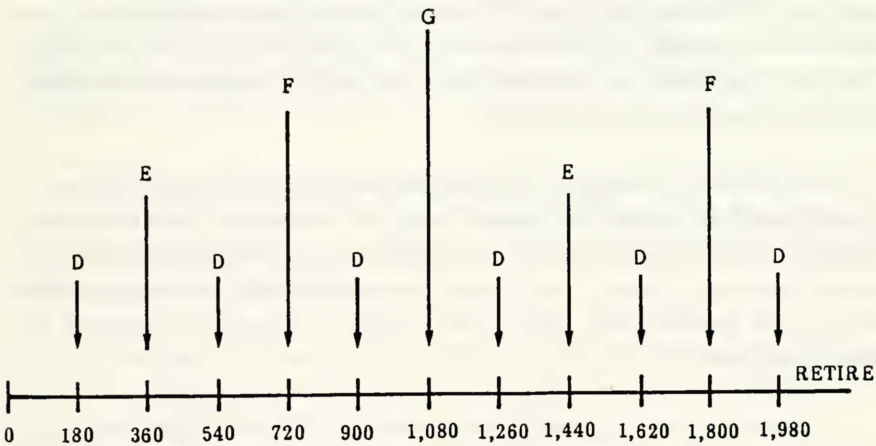


EXHIBIT 3-11
CAR OVERHAUL CYCLE



experience, improved cost estimates, and less risky bids. Each company was contracted to overhaul a married pair of R36 cars with Westinghouse propulsion and a married pair with GE propulsion.

With regard to the accomplishments of the capital improvement program which brought about the new overhaul schedule, the railcar improvement projects, and the railcar overhauls, NYCTA has estimated the improvement effects in terms of improved MDBF. Data availability appears to be a major obstacle to more definitive results but indications thus far show improvements of a magnitude that show a slight increase in MDBF over the 1980 level and greater improvement over projected levels in 1981 and 1982. In the opinion of NYCTA engineers this halt in the decline of MDBF is noticeable and expectations are high that MDBF will continue to increase.

3.4.2 PATCO Maintenance and Overhaul Experience

The Port Authority Transit Corporation (PATCO) is a relatively new transit system and has made only two railcar purchases. The original set of 75 railcars which opened service on the line in 1968 were built by the Budd Company. A second purchase of 46 railcars cars, built by Canadian Vickers under license to Budd, was made in 1977 although the cars were not put into service until late-1979 through mid-1981. The Budd cars are divided into two types: 25 singles and 50 doubles; while the Vickers cars are all doubles.

PATCO has a thorough car inspection and maintenance program which is funded through the maintenance budget. During the first week of each month each railcar is given a mechanical and an electrical inspection. The inspection normally takes 2 man-hours of effort. Small repairs and/or adjustments are made while the car is in the inspection line. More serious problems are shopped or scheduled for major repair time.

In addition, major inspections are performed at 12,000-mile intervals or at least every 4 months in the case of low mileage cars. These inspections are referred to as ABC inspections and are scheduled as follows:

A Inspection	-	12,000 miles or 4 months
B Inspection	-	36,000 miles
C Inspection	-	72,000 miles

There are mechanical and electrical components of these inspections.

These inspection intervals have evolved over time; when PATCO initiated service in 1969 it adopted a 6,000-mile interval for the A inspections. It was soon found that the 6,000-mile interval was too frequent; the interval was increased to 7,500 miles, then to 9,000 miles, and finally to 12,000 miles in 1972. This has proven to be optimum for, on occasion, cars would be missed and allowed to run up to 15,000 miles. When these cars were inspected they were found to need extensive work and far too many replacement items.

If cars are run principally in rush hour service they may not accumulate 12,000 miles in 4 months, so the 4-month time limit was also imposed; this is because some items degrade over time, regardless of mileage. Thus, active cars receive four inspections per year and less active cars receive three.

A lubrication schedule is included in the mechanical component of the A inspection and some lubricating is done at each interval. However, major lubrication is done annually during the fourth calendar quarter. At that time, gear-unit oil is replaced and traction motor bearings are greased.

PATCO has recently begun a heavy overhaul program on the Budd cars and is considering a light overhaul on the Vickers cars in the future. Like the inspections described above, overhauls and rebuilding are geared to accumulated car mileage. There are two types of overhauls:

D Overhaul: at approximately 300,000 miles the trucks and air brake components are rebuilt and the traction motors are overhauled, in addition to normal maintenance and repair.

E Overhaul: at approximately 800,000 miles, the D overhaul work is performed and, in addition, the car is rewired, all relays and electrical

equipment are rebuilt, windows replaced and the interior is brought back to new condition.

PATCO has initiated a project to upgrade the Budd cars and, in the process, will complete an E overhaul for these cars. The core of this overhaul and upgrading effort is a complete rewiring of the cars which will eliminate many equipment failure situations caused by dynamic braking and its heat-generating resistors; the neoprene rubber "car and locomotive wire and cable" used in 1968 cannot stand up to the heat and deteriorates. Thus, the upgrading of the wiring, with the concomitant opening of many electrical and mechanical components, paves the way for other routine overhaul tasks. In fact, the project involves 38 upgrade tasks, 16 routine overhaul tasks, and one other separately funded task to completely replace the Automatic Train Operation/Automatic Train Control package.

PATCO also has an annual air-conditioning inspection and an air-conditioning overhaul scheduled at about every 5-6 years. The complete schedule is shown in Exhibit 3-12.

EXHIBIT 3-12

PATCO INSPECTION AND OVERHAUL SCHEDULE

INSPECTION	SCHEDULE	COMMENTS
Monthly	Monthly	2 man-hours per car inspect/repair
A B	4 months 12 months	40 man-hours per car inspect/repair
C	24 months	56 man-hours per car inspect/repair
Air-conditioning	12 months	8 man-hours per car
OVERHAUL		
D	@300,000 mi.	trucks rebuilt: wheels replaced rebuild air brake components overhaul traction motors normal maintenance and repair
E	@800,000 mi.	all D overhaul work car rewire rebuild relays and electrical equipment replace windows rehab interior
Air-conditioning	about 5-6 years	40 man-hours per car

SOURCE: PATCO

3.4.3 SEPTA Maintenance and Overhaul Experience

The rapid rail system of the Southeastern Pennsylvania Transportation Authority (SEPTA) consists of two lines which do not interchange with each other; furthermore, each has a different gauge and a different third rail configuration so the cars are not interchangeable. Data from SEPTA for 1984 illustrate (Exhibit 3-13) the marked differences between two different fleets of equipment, the new Broad Street IV cars (of the Broad Street Subway line) purchased from Kawasaki in 1982-1983 and the older Market-Frankford (M-F) cars (of the Market Street Subway Elevated line) manufactured by Budd in 1960. The M-F cars represent a mixed fleet of overhauled and non-overhauled cars and show a lower availability when compared with the new Broad Street IV cars.

Maintenance and necessary overhauls of the M-F cars had generally been deferred since their purchase in 1960 by SEPTA's privately-owned predecessor. The grant application states that, concurrent with the purchase of the railcars, "due to mounting operating losses, the maintenance force for this fleet was reduced from a total work force of 300 to 65 people. This severe cutback was based on the erroneous assumption that the new cars would be maintenance free." As a result, by the late 1970s reliability had dropped to extremely low levels. The cars have accumulated more than 800,000 miles to date, a relatively low figure for their age, which may have been a factor in SEPTA's ability to keep them in service in spite of the lack of preventive maintenance and overhauls. (Although Budd recommended a 10-year overhaul, nothing was done at that time, i.e., 1970.)

In the late 1970s, SEPTA initiated a General Overhaul (GOH) program for the M-F cars to plan and implement an overhaul program to combat excessive maintenance costs and reduced reliability. Car reliability had fallen so low (see Exhibit 3-14) that a separate truck overhaul project was established within the GOH program effort. Its purpose was to get failing cars back in service and to forestall an alarming number of failures in service. This project continued independently from the GOH; nonetheless, GOH cars received rebuilt trucks as well.

The scope of the overall M-F GOH program consists of rehabilitation of the trucks; the control system; the Cineston controller; the pneumatic systems (door

EXHIBIT 3-13

MEAN DISTANCE BETWEEN FAILURE AT SEPTA

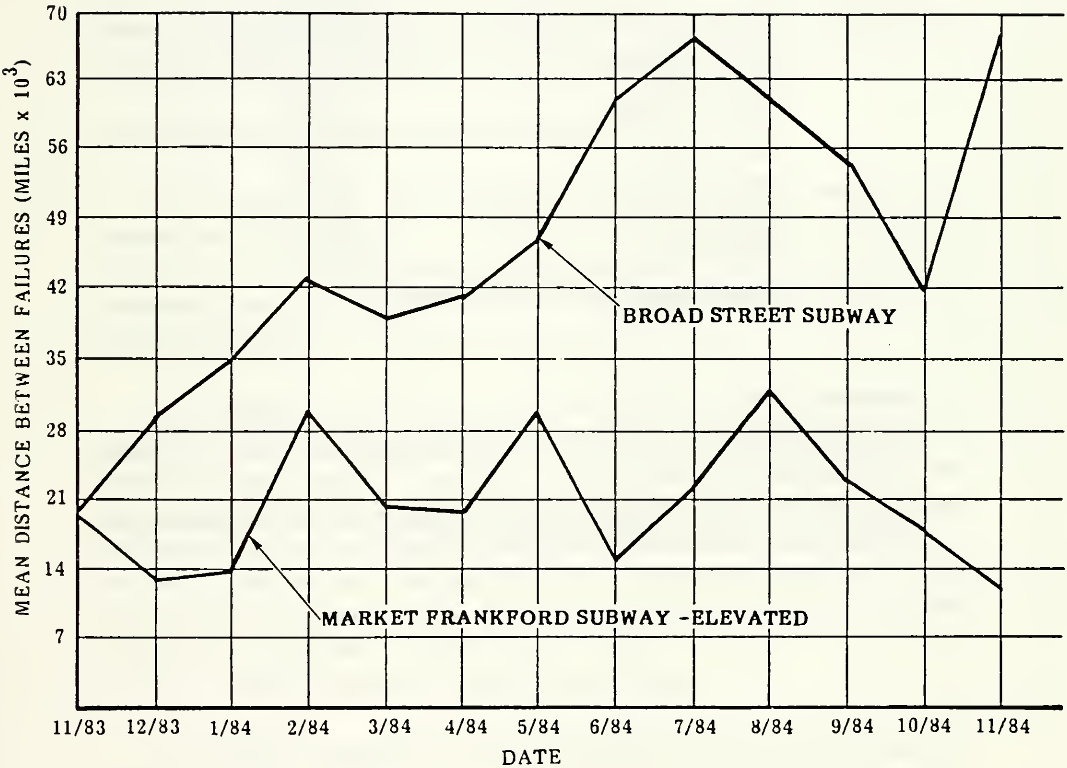


EXHIBIT 3-14

SEPTA RAILCAR RELIABILITY HISTORY

PERIOD	MEAN DISTANCE BETWEEN FAILURES* (MILES)
1960-1964	20,000
1964-1974	80,000
1975	65,000
1978-1979**	11,000 - 15,000
January 1980**	18,500
February 1980**	18,900
March 1980**	14,500
April 1980**	16,100
May 1980**	22,000
June 1980**	15,500

Annual mileage per car is 40,000 miles.

SOURCE: SEPTA

* SEPTA defines a failure as a mechanical problem which causes five or more minutes delay in service.

** Since 1978, the MDBF includes not only equipment problems, but also operator inexperience in dealing with mechanical problems.

operators, couplers, brakes and acceleration system); heating, lighting, and ventilation; carbody; and seating and passenger amenities. Phase I of this program provided for labor and materials required for a complete overhaul of 50 cars. Phase II provides for the overhaul of 200 cars as well as shop improvements.

Unfortunately, SEPTA's data does not distinguish between cars that have been overhauled and those that have not. Nonetheless, the GOH and truck overhaul efforts have resulted in reliability improvements. FY 84 data indicate that the MDBF on the Market-Frankford line was 22,655 miles compared to 16,459 miles in 1979, an improvement of about 38%. The goal for FY 85 is an MDBF of 28,000 miles. (A failure at SEPTA is an incident that causes a delay of 5 minutes or more and that could not be corrected within 5 minutes by persons on the line).

3.4.4 MBTA Maintenance and Overhaul Experience

The Massachusetts Bay Transportation Authority (MBTA) operates three separate rail rapid transit lines: the Red Line, the Orange Line, and the Blue Line. Each line operates virtually as an independent rail line and the cars are not interchangeable from line to line. The maintenance of each line is also organized and conducted separately.

The Orange Line, which currently operates 120 cars manufactured by Hawker-Siddeley in 1981 and 1982, has prepared a preventive maintenance schedule which includes routine inspections. Two cars are inspected each day, utilizing a foreman and 5 repairmen; average inspection mileage is 7,000 miles. During the inspection, all onboard systems are inspected, adjusted, tested, repaired or lubricated as required. In addition, every two years each car goes through a rating cycle in which motor currents, air brake cylinder pressures, acceleration rates, and line voltages are recorded during road tests; adjustments are made to the wheel slip/slide system, the brake pressure system and the potential relay setting.

The planned maintenance schedule also includes "programs" and overhauls. At MBTA a program is a periodic preventive maintenance activity that is performed on each of the vehicles; in an overhaul rebuildable vehicle components are removed, rebuilt in a shop and replaced as required. Exhibit 3-15 presents the program

EXHIBIT 3-15

MBTA ORANGE LINE
MAINTENANCE PROGRAM SCHEDULE

	Man-Hours Per Fleet
A. Annual Program Items	
1. Blow out dust from motors and controls	720
2. Clean condensers	240
3. Lubricate side and end doors	480
4. Service compressor dryers and crankcases	480
5. Service cab heater blowers	120
6. Service body heater blowers	960
7. Change transmission oil	480
8. Clean shoe beams	480
B. Tri-Annual Program Items	
1. Replace axle ground brushes	480
2. Change A/C Compressor oil	480
3. Calibrate line breakers	960

SOURCE: MBTA

EXHIBIT 3-16

TENTATIVE LIST OF MBTA ORANGE LINE PLANNED OVERHAULS

	VEHICLE COMPONENT	PERIOD	MAN-HOURS FOR FLEET*
1.	Air brake valves	3 years	2,880
2.	Motor generators	4 years	1,920
3.	A/C Compressors and motors	5 years	2,880
4.	Coupler controls	5 years	1,200
5.	Suspensions	5 years	2,880
6.	Motorman's seats	5 years	1,200
7.	A/C solenoid valves	5 years	960
8.	Cab windows	5 years	1,920
9.	Traction motors and couplers	6 years	3,840
10.	Air compressors	6 years	720
11.	Overhead blower motors	6 years	1,920
12.	Coupler slides (consumable parts)	7 years	1,920
13.	Propulsion controller cams and line breaker	8 years	9,600
14.	Door operators	8 years	4,800
15.	Transmission units	8 years	3,840
16.	Tread brake units	10 years	3,840
17.	Couplers	10 years	3,840
18.	Cinestons	10 years	1,920
19.	Floors	10 years	6,000

SOURCE: MBTA

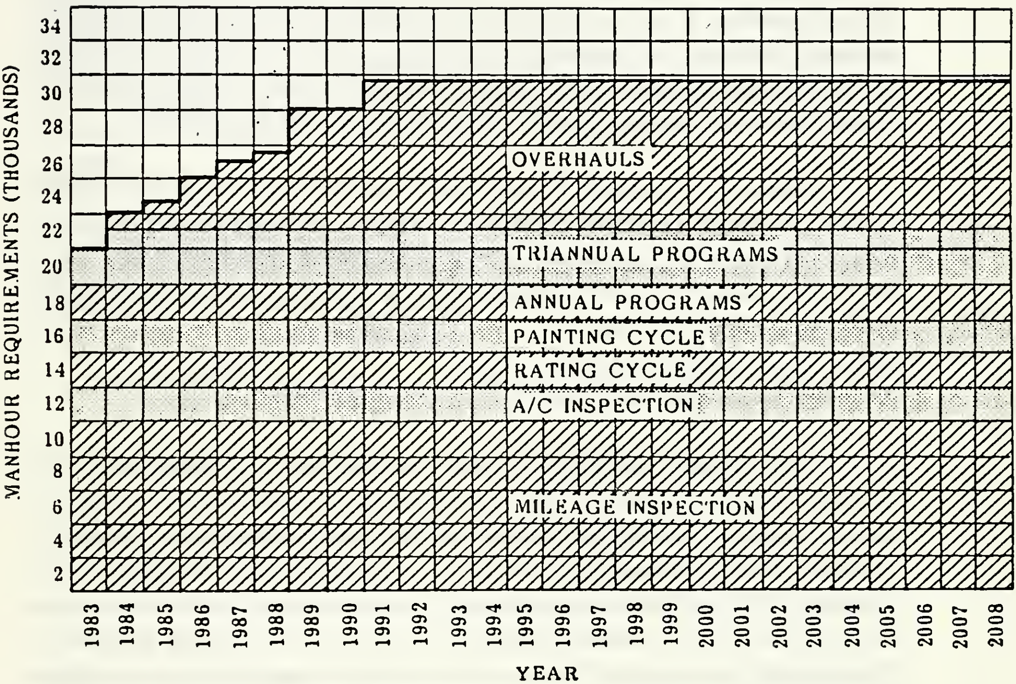
* Fleet size = 120 cars; remove and replace with like component; rebuild hours are additional.

schedule together with preliminary manpower estimates. Exhibit 3-16 provides a tentative list of planned overhauls for rebuildable vehicle components. It can be seen from this list that the Orange Line planned overhaul program is much like the progressive maintenance approach discussed in Section 3.1. The projected labor requirements for these preventive maintenance measures together with routine painting and air conditioning inspection cycles is given in Exhibit 3-17. This projection is based upon current plans and is not necessarily supported by budgeted programs.

The MBTA has had recent experience with railcar overhauls. The Red Line South Shore cars, both single and married pair units, have undergone a truck and suspension overhaul. The Red Line Cambridge-Dorchester (C-D) cars were recently rebuilt, 34 in-house and 50 by General Electric in Boston. Both overhauls were undertaken as the result of a need to improve equipment reliability and maintainability rather than as a part of a larger preventive maintenance and overhaul schedule. Our discussions with MBTA indicated that there was no attempt to determine before-and-after reliability and/or maintainability values for this equipment.

EXHIBIT 3-17

ORANGE LINE PREVENTIVE MAINTENANCE LABOR PROJECTIONS



* SOURCE: MBTA

3.5 FEDERAL FUNDING REQUIREMENTS AND THEIR IMPACT UPON OVERHAUL/REBUILD DECISIONS

Current guidelines regarding federal funding eligibility that apply to railcar equipment overhaul/rebuild are contained in UMTA Circular 9030.1, dated June 27, 1983. This document presents guidelines for the preparation of grant applications under the Section 9 (of the 1982 Surface Transportation Act) formula assistance program. Although the American Public Transit Association (APTA) has indicated that these guidelines are limiting and has suggested significant changes through a formal review and response process, the guidelines are currently in effect.

In addition, the proposed Federal Fiscal Year 1986 (FFY 86) Budget includes substantial reductions in federal assistance to transit. Although the FFY 86 Budget may not be enacted in its proposed form, it is likely that cutbacks will be made in 1986 and continued in the near future. Details on these two items and their impact upon CTA are discussed below.

3.5.1 Section 9 Grant Limitations

UMTA Circular 9030.1 which was issued on June 27, 1983 indicates that Section 9 grants "will become the primary source of Federal funds for routine capital assistance needs, that is, bus and rail system replacements, equipment purchases, facility construction, and system modernization and rehabilitation." This wording implies that railcar overhaul/rehab work can be funded by Section 9 grants but Appendix D -- Acquisition of Spare Parts -- of the Circular provides an interpretation of terminology which severely limits the items which can be funded under Section 9. In addition, railcar rehabilitation requirements state the following specifically:

1. Rehabilitation must be more cost-effective than new vehicle purchase;
2. Service life must be extended 40% of the vehicle's original life;
3. The vehicle must be at the end of its useful life; and
4. No routine maintenance or repair can be capitalized.

Further, although UMTA has funded the upgrade elements of a vehicle overhaul (for example, the current PATCO project) the Circular indicates that UMTA considers

vehicle overhauls as routine maintenance, and therefore ineligible for Federal assistance.

In response to these guidelines, APTA has argued that rehabilitation of railcar rolling stock "which results in betterments or improvements" should be considered at anytime for eligibility under Section 9. Moreover, recognizing that "major vehicle components and subsystems have substantially different useful lives than vehicle bodies and frames", APTA has suggested that the rehabilitation or replacement of major subsystems or components may be eligible if the normal service life of such subsystems or components has been reached or maintenance parts are no longer available.

UMTA has since responded to the industry with proposed revisions to the rolling stock grant requirements; these revisions include the following positive aspects relevant to a CTA railcar overhaul:

1. Eligibility for vehicle replacement, mid-life overhaul and/or rebuild funding before the end of a railcar's useful life;

2. Reduction in the specified minimum useful life for rail vehicles;

3. Deletion of any rail vehicle spare ratio requirements.

The revisions state that although railcar improvements or replacement are eligible for capital funding prior to the end of a railcar's life, actual Federal funding participation will be reduced from the maximum 80/20 to something less, on a pro-rata basis, based on actual age of the railcar vs. the standard useful life. The actual Federal share of the cost of the major subsystem replacement or rehabilitation will be 40% for a 12-year old railcar. For each year of railcar age beyond twelve years, the Federal share will increase by 3%, but will not exceed 80%.

3.5.2 Summary of the Proposed UMTA 1986 Budget

The Federal Fiscal Year 1986 (FFY 86) UMTA budget submitted to Congress by the Reagan Administration proposes a total of $1.377 billion for transit. The

FFY 85 budget was $4.131 billion; thus, the proposed FFY 86 budget cut for UMTA approaches 67%.

The proposed FFY 86 budget would eliminate all general fund expenditures for transit (the Section 3 discretionary funds) effectively eliminating any new rail system starts. Thus, the only remaining funding would be approximately $1.1 billion, which would come from the one cent gasoline tax, and approximately $27 million in administrative expenses. (The $1.1 billion estimate from the gasoline tax may be low; some estimates put it at $1.3 billion.) This would effect a reduction in real dollars. Exhibit 3-18 attempts to put the FFY 86 Budget into perspective.

In addition to the decrease in Federal support, the budget proposes an increase in the local matching share from 25% to 30%. Although this will make the total dollars larger, it puts an additional burden on the local transit authorities.

In testimony before the Senate Appropriations Subcommittee on Transportation on February 21, 1985, the Secretary of Transportation, Mrs. Dole, stated, "Except for grants to Washington Metro, which will continue at the 1985 level until Stark-Harris authorization is exhausted, all transit grants would therefore be financed from one cent of the Federal tax on highway motor fuels, consistent with the Administration's goal of funding the bulk of Federal transportation assistance through user fees. The formula grants would be available to finance planning, capital replacement, rehabilitation, and improvement projects. Effective in FFY 86, Federal funding would no longer be available for transit operating costs, since this matter is best addressed by local management through local decision-making and local financing."

This statement indicates that an additional burden will fall on transit authorities that have been utilizing Section 9 funds for operating assistance. It should be pointed out that the FFY 86 budget proposal was not well received by the Congress and that initial reaction noted that the percentage reduction in the UMTA budget was far below that of other agencies in DOT. The Secretary has stated that the Administration would be willing to consider some operating assistance provided it was used for non-labor related items.

EXHIBIT 3-18

URBAN MASS TRANSIT ADMINISTRATION FUNDING

(in thousands of dollars)

Budget Authority	'84 Actual	'85 Estimate	'86 Estimate
Admin. Expenses	29,400	30,735	26,810
Research Training & Human Resources	54,800	51,000	--
Interstate Transfer Grants (Transit)	295,400	250,000	--
Washington Metro	250,000	250,000	250,000
Formula Grants (Section 9)	2,388,592	2,449,500	--
Formula Capital Grants (Trust Fund) (Section 9)	--	--	1,100,000
Discretionary Grants (Trust Fund) (Section 9)	1,250,000	1,100,000	--
TOTAL	4,268,192	4,131,235	1,376,810

In summary, the FFY 86 budget for transit is not a promising one, since compromises on the Administration proposals are still likely to result in reductions from previous levels. Congress, by virtue of the mandated Rail Modernization Study which is nearing completion, has recognized the need to assess the states of rail transit equipment in the U.S. It remains to be seen how much support (funding) it will give to the modernization effort outlined therein and which items will be capitalized.

3.6 IMPLICATIONS RELATIVE TO CTA PRACTICE AND PLANS

Preventive maintenance is intended to prevent and/or anticipate failures by subjecting a railcar to periodic inspection and replacing or repairing anything found to be defective. Procedurally the inspection must be more than a quick look or "walkaround". Mechanical items can be checked with "go-no go" gauges. Electrical items can be checked by measurements and/or performance. Each subsystem should have its own method and these methods can readily use listening tests (as described in Section 3.1) or other methods that are part of responsive maintenance.

Transit equipment and maintenance engineers generally have some failure data on the life of certain subsystems, either by time or mileage. This information may be used to schedule replacements within the inspection cycle. Progressive maintenance actions such as scheduled replacement of braking system components have long been ICC-FRA requirements for railroad service and make good economic sense as well because in-service brake failures will have high costs and include the possibility of a severe accident.

Deferred maintenance has the effect of reducing maintenance costs, but only for a limited time. Eventually, the poorly maintained equipment begins to perform poorly, resulting in reduced reliability, reduced dependability, and user dissatisfaction. Failures in service will increase, as will repairs and/or replacements of failed or damaged components; such repairs cost more than preventive maintenance. If maintenance budgets are frozen or continue to be reduced, equipment deterioration will continue at an increasing rate.

CTA has a well-established preventive maintenance inspection program based on a 6,000-mile interval; it has a lubrication schedule in conjunction with the inspection. The CTA all-electric railcar is relatively simple, an advantage for maintanance as illustrated by CTA's relatively low maintenance cost per car/mile; this simplicity has been carried over to the new 2600-series purchase.

It is apparent that higher order inspections, such as an annual inspection, should be established at CTA, possibly along the lines of those at NYCTA or

PATCO; this will enable a more extensive inspection to be performed as appropriate. Additional responsive and progressive maintenance tasks can be worked into the program as well. By progressive repairs, or overhaul, of components off the car, at CTA or contractor shops, many components or subsystems can be changed out while a railcar is out of service for a short time. Many railcar components can be rehabilitated in this manner.

In order to reduce failures in service and improve equipment reliability, it is necessary to carry out some light and heavy overhaul work. In principle, these work elements must be examined to identify the appropriate intervals between overhaul/change-out for each component or subsystem of each car series. Then items of similar periods should be grouped so that a schedule can be established to remove and replace then in that interval. A major work item, such as a truck rebuild or car rewiring (at PATCO), may be a controlling schedule factor which forces a car to be shopped for a specific length of time. Traction motors may also be a critical element; if they are not overhauled at an appropriate interval, a slow breakdown of insulation will occur which might not be detected until a large amount of moisture is drawn into the units, resulting in an epidemic of failures. Occurrences of this type have already led to major interruptions at CTA.

CTA engineers have made proposals regarding car rehabilitation and car maintenance which are reasonable in view of other recent transit authority practice, particularly at NYCTA and SEPTA. Engineering experience in general and transit authority experience in particular underscores the need for preventive maintenance for electrical and mechanical equipment if it is to achieve its design life without excessive maintenance costs. Moreover, it is not always possible to reverse the steady deterioration of railcar equipment through massive overhaul or rebuilding efforts in a cost effective manner.

The implementation of the CTA proposals requires a substantial local financial commitment, particularly in view of current (and proposed) UMTA funding limitations. The best hope for Federal assistance is to carefully examine each individual overhaul effort in terms of potential upgrading of the equipment since UMTA does provide financial support for such activities. The PATCO experience shows that substantial improvements can be made to railcar equipment through a combination

of upgrade and overhaul work items. Further analyses are necessary to accurately estimate the potential upgrade items for the CTA railcars.

On the basis of the proposals prepared by CTA engineers, a cost summary has been prepared for the ten-year period, 1986-1995 and is shown in Exhibit 3-19. The CTA cost estimates for a 5-year heavy maintenance and a 10-year overhaul have been used and escalated to 1985 dollars. In view of the proposed work these estimates are in line with the experiences at other transit authorities. Closer examination and tear-down of individual railcars, as was done by NYCTA, may reveal the need for changing the cost estimates, either up or down. Nevertheless these cost estimates are useful for discussion purposes. As can be seen from the exhibit, the financial commitment would be substantial, a total of $363.2 million (1985 dollars) over the next 10 years. The extent of the CTA commitment can only be determined after a more careful examination of the railcars and an assessment of the upgrade potential. Such a commitment will, however, yield improvements in service, extend the useful life of the railcar equipment, and reduce failures in service. Also, as will be seen in Section 5.0, the investment will also yield some reductions in preventive maintenance costs as well.

EXHIBIT 3-19

COST ESTIMATE FOR PROPOSED CTA 5-YEAR HEAVY MAINTENANCE (M) AND 10-YEAR OVERHAUL (R) PROJECTS

Car Series \ Year	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
2000(1) 176										
2200(2) 144	R(60)*	R(84)				M(60)	M(84)			
2400(3) 194			R(120)	R(74)				M(120)	M(74)	
2600(3) 600		M(120)	M(120)	M(120)	M(120)	M(120)	R(120)	R(120)	R(120)	R(120)
CTA Cost Estimates	Annual Costs (millions $)									
M @ $74,200(4)		8.9	8.9	8.9	8.9	13.4	6.2	8.9	5.5	
R @ $360,400(4)	21.6	30.3	43.2	26.7	--	--	43.2	43.2	43.2	43.2
TOTAL	21.6	39.2	52.1	34.6	8.9	13.4	44.4	52.1	48.7	43.2

* Numbers in parentheses represent number of cars proposed for heavy maintenance (M) or overhaul (R).

(1) CTA has decided that it would not be cost effective to overhaul the 2000-series cars.

(2) Assumes that it would take about 12 calendar months (from June 1, 1985) to begin actual overhaul rate at 10 cars per month.

(3) Assumes a rate of 10 cars per month.

(4) 1983 CTA cost estimates factored by a 1.06 inflation factor for 1985 dollars. A heavy maintenance program for the 2200-Series was not budgeted at the 5-year point; the overhaul in 1986-7 will be a major effort for the 15-year old cars. The overhaul for the 2400-Series will occur when the cars are 10 years old but they will not have had a 5-year heavy maintenance program.

4.0 CTA RAILCAR PERFORMANCE EVALUATION

Railcar performance is usually indicated by its reliability, maintainability and the associated operation and maintenance costs. Reliability is defined as the probability that an equipment will operate in a satisfactory manner for a specified period of time when used under stated conditions. It is often expressed in terms of mean time between failure (MTBF) or the equipment failure rate. On the other hand, maintainability is an inherent characteristic of equipment design and installation and is concerned with the ease, economy, safety, and accuracy with which maintenance actions are performed. It is measured by maintenance times and maintenance costs and is often expressed in terms of the mean time to repair (MTTR) the equipment.

Reliability, maintainability, and costs -- these are therefore the necessary ingredients for evaluating the performance of CTA railcar fleet. Some of the CTA fleet are not addressed in this task for the following reasons. The 5-50 Series cars are currently being rebuilt by Morrison-Knudsen and the first set of completed cars are scheduled back in Chicago this year. The 6000-Series (some of which are over 30 years old) are scheduled to be replaced with new 2600-Series cars. A small number of the 6000-Series cars are slated for an overhaul at Skokie shop. CTA has decided not to perform any overhaul or rehab work on the 2000-Series which have been a serious maintenance problem since they were delivered; a rehab on these cars is not considered to be cost-effective. Hence, only the performance of the 2200-, 2400-, and 2600-Series cars are addressed in this study. It should be noted that the 2600-Series cars are still being delivered to CTA; nevertheless, it is interesting to contrast this new equipment with the older 2200- and 2400-Series.

4.1 DESCRIPTION OF DATA REQUIREMENTS

Major reliability/maintainability factors required to evaluate CTA railcar performance are defined below:

Mean Time Between Failure (MTBF) is given by

$$MTBF = \frac{H_s}{N_f}$$

where H_s = car-hrs scheduled during period under investigation

N_f = number of failures experienced during the same period.

Mean Time Between Inspections (MTBI) is given by the following relationship

$$MTBI = \frac{H_s}{N_i}$$

where N_i = number of inspections during period

Mean Time Between Maintenance Actions (MTBM) is defined as

$$MTBM = \frac{H_s}{N_m}$$

where N_m = total number of maintenance actions for period

Also $$MTBM = \frac{1}{1/MTBF + 1/MTBI}$$

Mean Time To Repair (MTTR). Mean (or average) elapsed time required to perform unscheduled maintenance actions is given by

$$MTTR = \frac{D_s}{N_f}$$

where D_s = total repair time for all failures or unscheduled maintenance actions experienced during the period

Mean Time To Inspect (MTTI). Mean (or average) elapsed time to perform scheduled inspection is given by

$$MTTI = \frac{D_i}{N_i}$$

where D_i = total inspection time during period

Mean Time To Maintain (MTTM). Mean (or average) elapsed time required to perform both unscheduled and scheduled maintenance actions.

$$MTTM = \frac{D_m}{N_m}$$

where D_m = cumulative elapsed time for both preventive and corrective maintenance

Mean Time To Restore (R_e). Mean (or average) elapsed time required to repair, restore, and/or retain a car in full operational status is represented by

$$R_e = \frac{D}{N_m}$$

where D = cumulative restore time including on-line downtime, retrieval time, time during which car is in the yard waiting repair/maintenance, time during which car is actually worked on, and time to inspect and approve the repair/maintenance prior to certification for operational readiness.

Fleet Availability (A_v) is the probability that the fleet will operate satisfactorily at any point in time. Availability is used as a means of measuring equipment reliability and maintainability and applies to both unscheduled and scheduled maintenance. It is expressed as

$$A_v = \frac{MTBM}{MTBM + R_e}$$

where all parameters are as defined earlier.

In addition to the above, other types of data required to evaluate railcar performance include maintenance costs broken down between labor and material functions, fleet size, number of cars required to meet different service levels, and the system operational schedule. All of these data would have to be available over a specified period of time and for each individual car series under investigation.

4.2 DATA AVAILABLE AT CTA

Review of the data requirements identified in the preceding section points to the potential problems with any effort to conduct a comprehensive evaluation of the performance of transit equipment. These problems are related to the fact that all the data items needed to determine the above performance indicators are not routinely collected at a majority of U.S. rail transit authorities. Where they are maintained at all, the format, frequency, and scope of these data items vary significantly between transit authorities that substantial data reduction would be required to make existing data bank meaningful. Because of existing dearth in reliability/maintainability information, the success of rail transit performance evaluation is, to say the least, difficult. Many transit authorities maintain that the benefits from extensive and consistent data collection do not justify the expense needed to maintain such a data bank. (CTA has recently implemented a new MMIS which is currently being debugged. This program should be a valuable source for future maintenance and reliability information and data.)

CTA is no exception to the problems with reliability/maintainability information discussed above. The only routinely collected maintenance information available is a chronological log of car failures/maintenance actions. This log is accumulated on a car-by-car basis in a computer data file called Railcar History. Railcar histories are usually available on-line for a period of six months after which they are transferred into a related data base (not on line) called the VMT.*

CTA car histories include unscheduled and scheduled maintenance actions for individual cars in the fleet. The logs also contain brief descriptions of the types of failures experienced as well as times which indicate when the reports were logged in and out of the computer. Except for information about the cars which experienced particular failures, none of the data contained in this data file was helpful in establishing the reliability of the equipment. In addition, since times recorded in this data file are not indicative of actual repair times for failures, equipment maintainability could also not be established on the basis of this file

* The acronym VMT originated with CTA's bus MMIS and actually stands for Vehicle Maintenance - Terminal in that system.

alone. Another problem with using the car history data relates to the problem of "wrong calls". Normally, when a car fails in service, the identity of the car that is logged in the railcar history is that of the lead car in a multiple-car train, although this car may not be the one that experienced the failure. This introduces significant problems with any attempt to study the performance of individual car series since the appropriate number of maintenance actions for a specific car cannot be accurately determined. The other problem involves the description of failures in the car histories. The computer operator only identifies maintenance actions on the basis of information received from line reports. However, maintenance actions are logged by job numbers which correspond to major work categories established at CTA. Hence, car failures can always be related to major car subsystems.

The major work categories and their respective codes in the data files include:

	Work Category (Code)	Car Components
o	Propulsion (1000)	traction motors, traction power controls
o	Car Body (2000)	car structure, windows, seats, destination signs, lighting systems, coupler and drawbar, and such activities as battery-charging, convertor/motor generator/motor alternator repairs, and maintenance of safety equipment.
o	Brake System (3000)	electronic components, track brakes, etc.
o	Doors/Communications (4000)	door elements, controls, and communication equipment.
o	Heating, ventilation and air conditioning (5000).	
o	Trucks and wheel assemblies (6000).	
o	Planned Maintenance Program (7000).	scheduled car inspections.
o	General terminal work (8000).	
o	Automatic Train Control (9000)	including all signal work.

The VMT report which is routinely compiled from car histories also does not contain data on repair times. However, they go one step further than railcar histories in that they attempt to reconcile problems of "wrong calls" and incorrect failure descriptions by establishing two distinct "segments" of the report -- one for "problem reported" and the other for "problem found".

Delays in service are routinely collected in line logs by the Operations Division. These logs identify all incidents that result in service delays. Delays are also identified by probable cause including vehicle failure, power and signal problems, crime, and any other non-system-related cause. However, because these data are not correlated with repair actions, they could not be used for this study.

CTA keeps extensive maintenance cost information for each series of cars in the fleet. Maintenance costs are summarized monthly in the Vehicle Series Report under two major categories -- maintenance that is performed at the rail terminals and maintenance performed at the shop areas, for example, parts rebuilding. Monthly records for total rail maintenance for both labor and material functions can be generated from these data. Costs are generally broken down by car series when possible. When costs cannot be identified by vehicle series, they are listed as unassigned in the Vehicle Series Summary.

4.3 RESULTS OF DATA REDUCTION EFFORTS

Considerable data reduction was performed in order to use available data to establish current performance levels for each of the three car series under study. The data reduction effort was supplemented by information generated from extensive discussions with CTA maintenance personnel as well as estimates and assumptions made by the study team. In general, data items were broken into three major categories -- maintenance data, system operational data, and maintenance cost information.

4.3.1 Maintenance Data

Because VMTs were only available for the first half of 1984, railcar histories and VMTs were combined to reflect the performance of the 2200-, 2400-, and 2600-Series for one year period. These data included all maintenance actions during the year for a randomly-selected sample consisting of ten 2200-Series cars, ten 2400-Series cars, and eight 2600-Series cars. VMT data covered the period January - May 1984 and railcar histories covered the period June - December 1984.

Since neither of these records include any information on repair times, the study team obtained three independent estimates of repair times for typical types of failure for each car series. CTA railcars are maintained at eleven inspection and maintenance shops (see Section 6.0). Repair times at these shops vary as a result of the differences in available manpower and facilities. Hence, any estimates of times must recognize these variations. Based on the independent estimates obtained from CTA maintenance personnel, repair times were generated for all failures experienced by each car in the sample. These times were then accumulated for the period under investigation. Information on all maintenance actions for the sample data is summarized in Exhibit 4-1. The number of maintenance actions include both unscheduled and scheduled maintenance (inspections). Repair times are based on an average of two men per repair action. Times for routine inspections are based on an estimate of 4 hours per inspection with 6 people performing each inspection activity.

In addition to car maintenance actions, subsystem failure distribution and corresponding repair times were also generated. These are summmarized in

EXHIBIT 4-1

SUMMARY OF EQUIPMENT MAINTENANCE ACTIONS FOR RAILCAR SAMPLE

DATA ITEM	2200-SERIES	2400-SERIES	2600-SERIES
Sample Size	10	10	8
Number of Failures	485	476	275
Number of Inspections	71	64	48
Number of Maintenance Actions	556	540	323
Repair Time (hrs)	430	330	182
Inspection Time (hrs)	284	256	192
Maintenance Time (hrs)	714	586	374

Note

Fleet Size: 2200-Series = 144 railcars; 2400-Series = 194 railcars; 2600-series = 250 railcars at time of data collection.

Exhibit 4-2. Major subsystems covered include propulsion, car body, brakes, doors/ communications, HVAC, truck and ATC in acordance with work categories established at CTA. Subsystem failure and repair data are based on a sample size consisting of five 2200-, five 2400-, and four 2600-Series cars because of the extent of the necessary data reduction.

4.3.2 System Operational Data

System operational data obtained from CTA include information on system-wide assignment of railcars to various routes. This assignment is summarized in Exhibit 4-3 which also shows a breakdown by lines of the total number of cars required for service, number scheduled for maintenance, and the number in reserve. This breakdown does not disagreggate number of cars required for service by car series. Hence, estimates of railcar requirements by car series must be made from which car-hours scheduled can be calculated on the basis of operational schedules. Once the car-hours scheduled for service are calculated for each series, they can form the basis for estimating both the mean time between failure and the mean time between maintenance actions.

The number of 2200-, 2400-, and 2600-Series cars required for service has been estimated by considering only those lines on which these cars are assigned. For example, Exhibit 4-3 shows that the 2200-Series cars are assigned on the West-Northwest line only; the 2400-Series operate on West-South and North-South lines; the 2600-Series are assigned on West-Northwest, West-South and Ravenswood lines. Assuming that all cars on a particular line have an equal chance of being scheduled for service, the number of 2200-, 2400-, and 2600-Series cars needed for service can be calculated; the results are as shown in Exhibit 4-4 Detailed calculations of these numbers are contained in Appendix B.

Railcar requirements by period of day, as furnished by CTA, are shown in Exhibit 4-5. Original data show two requirement levels -- rush and base. The owl requirement has been estimated on the basis of one-third the base requirement. Based on total fleet requirement by period of day and the calculated number of cars scheduled for service, car-hours scheduled per day was calculated for each of the three series. These are summarized in Exhibit 4-6 for weekday and weekend/holiday

EXHIBIT 4-2

SUMMARY OF SUBSYSTEM FAILURE DISTRIBUTION AND REPAIR TIMES FOR RAILCAR SAMPLE

SUBSYSTEMS	2200-SERIES		2400-SERIES		2600-SERIES	
	NUMBER OF FAILURES	REPAIR TIME (HRS)	NUMBER OF FAILURES	REPAIR TIME (HRS)	NUMBER OF FAILURES	REPAIR TIME (HRS)
Propulsion	44	81.5	61	42.0	17	9.5
Car Body	56	28.0	40	22.5	27	19.0
Brakes	34	28.5	41	32.0	21	20.5
Doors and Communications	59	41.5	48	22.5	53	26.5
HVAC	25	14.5	9	6.0	12	6.5
Trucks	6	7.0	3	6.5	4	2.5
ATC	26	19.5	26	19.0	13	10.5

EXHIBIT 4-3

RAILCAR ASSIGNMENT (number of cars)

	LINES						
CAR SERIES	West-Northwest	West-South	North-South	Ravenswood	Evanston	Skokie Swift	Total
2000 (Pullman)	---	22	154	--	--	--	176
2200 (Budd)	144	---	---	--	--	--	144
2400 (Boeing	---	172	22	--	--	--	194
2600 (Budd)	138	72	---	40	--	--	250
5-50 (St. Louis)	---	---	---	--	37	7	44
51-54 (St.Louis/Pullman)	---	---	---	--	--	4	4
6000 (St. Louis	102	---	154	76	44	--	376
Required for Service	280	216	224	96	66	5	887
Scheduled Maintenance	10	8	10	2	2	1	33
Subtotal	290	224	234	98	68	6	920
Unassigned Reserve	94	42	96	18	13	5	268
Percent Reserve	24	16	29	16	16	45	23
Total Assigned	384	266	330	116	81	11	1,188

SOURCE: CTA Railcar Assignment dated March 9, 1984

EXHIBIT 4-4

ESTIMATED NUMBER OF CARS NEEDED FOR SERVICE

CAR SERIES	ROUTE				TOTAL REQD FOR SERVICE*	CURRENT FLEET SIZE
	W-NW	W-S	N-S	RAVENSWOOD		
2200	106	--	--	--	106	144
2400	--	140	16	--	156	194
2600	100	58	--	34	192	250

*Adjusted to account for assignment by married pairs.

EXHIBIT 4-5

FLEET REQUIREMENT BY PERIOD OF DAY

ROUTE	EQUIPMENT REQUIRED (CARS)		
	RUSH	BASE	OWL
Evanston Express	66	6	0
Evanston Shuttle	0	8	2
North-South	224	104	20
Ravenswood	96	32	0
Skokie Swift	5	2	0
West-Northwest	280	104	12
West-South	224	96	8
	895	352	42

SOURCE: CTA data as per March 18, 1984

EXHIBIT 4-6

CALCULATED CAR-HOURS SCHEDULED PER DAY

CAR SERIES	WEEKDAY SERVICE	WEEKEND/HOLIDAY SERVICE
2200	1,044	756
2400	1,533	1,100
2600	1,884	1,362

SOURCE: Based upon the estimated number of cars needed for service in Exhibit 4-4 and the fleet requirement by period of day in Exhibit 4-5; detailed calculations in Appendix B.

schedules. These calculations translate to the following annual car-hours requirement by series. (See detailed calculations in Appendix B.)

Series	Estimated Annual Car-Hours
2200-Series	349,000
2400-Series	512,000
2600-Series	629,000

It is important to reiterate that these calculations have been based on the assumption that each car has an equal chance of being scheduled for service. There may be other considerations which affect this assumption but the scope of this study did not permit more detailed analyses of this aspect. Moreover, iterative analyses based on estimated availabilities for each car series showed that the final results of the analyses are not siginficantly affected by the original assumption.

4.3.3 Maintenance Cost Data

Monthly records of maintenance costs summarized by car series were compiled by the Financial Services Department of CTA. These records also disaggregate maintenance costs by function, i.e., labor, material, and other. Costs which are not readily allocable to car series are identified as unassigned in these records. The breakdown in the Vehicle Series Summaries, as they are called, were used to generate adjusted maintenance costs for this analysis. The results are summarized in Exhibit 4-7 for the three railcar series over a period of one year. The adjustments reflect amounts that were unassigned to car series in the original data source.

EXHIBIT 4-7

ADJUSTED MAINTENANCE COST
(in dollars)

	2200 SERIES			2400 SERIES			2600 SERIES		
PERIOD '84	LABOR	MATERIALS	TOTAL	LABOR	MATERIALS	TOTAL	LABOR	MATERIALS	TOTAL
1st	86,820	88,526	175,346	155,590	181,587	337,177	137,774	100,664	238,438
2nd	96,101	154,020	250,121	159,638	192,067	351,705	136,160	97,081	233,241
3rd	106,192	278,680	384,872	181,091	341,963	523,054	190,715	127,505	318,220
4th	90,426	67,125	157,551	167,359	(6,618)	160,741	148,939	(28,855)	120,084
5th	81,557	142,513	224,070	187,391	87,180	274,571	131,892	191,326	323,218
6th	99,919	372,056	471,975	191,641	218,420	410,061	170,211	110,385	280,596
7th	95,802	193,908	289,710	104,228	187,680	291,908	182,321	88,352	270,673
8th	81,178	57,714	138,892	125,754	76,810	202,564	182,975	114,332	297,307
9th	99,799	220,034	319,833	158,460	239,181	397,641	238,085	(72,252)	165,833
10th	83,065	(61,794)	21,271	150,698	258,601	409,299	201,116	(61,757)	139,359
11th	81,463	121,835	203,298	123,417	94,539	217,956	203,045	141,831	344,876
12th	101,776	95,442	197,218	162,349	165,869	328,218	247,254	270,955	518,209
TOTAL	1,104,098	1,730,059	2,834,157	1,867,616	2,037,279	3,904,895	2,170,487	1,079,567	3,250,054

4.4 CURRENT RELIABILITY AND MAINTAINABILITY STATUS

4.4.1 Fleet Availability

The availability of each car series is determined by its reliability and maintainability status. To establish current reliability and maintainability, failure and maintenance time data generated for the fleet sample were extrapolated to reflect all cars in each fleet. The extrapolation procedure assumes that the entire fleet is operable and that all cars in each fleet are circulated as required. Details of the extrapolation procedure are presented in Appendix C.

Exhibit 4-8 summarizes the extrapolated maintenance data for the three series for the year 1984. Using these data, reliability/maintainability factors for each series have been calculated. These are summarized in Exhibit 4-9. Because of the scarcity of data, mean time to restore (R_e) has been estimated from results of an earlier study (see Ref. 1). Based on the estimated values of mean time to restore and the mean time between maintenance, fleet availabilities for the 2200-, 2400-, and 2600-Series have been calculated as 80 percent, 86 percent, and 89 percent respectively. These translate to the following estimated fleet size requirements:

Series	Estimated fleet size requirement (cars)
2200	134 (including 28 spares)
2400	182 (including 26 spares)
2600	216 (including 24 spares)

It is important to recognize some implications of the factors derived in Exhibit 4-9. The reliability (MTBF) of the 2600-Series cars is considerably higher than for the older cars despite the fact that the 2600-Series cars appear to be less frequently inspected. Mean time to repair the 2200-Series cars is approximately 30 percent higher than for the other series. This is probably a result of the relative age of this particular equipment.

EXHIBIT 4-8

SUMMARY OF EXTRAPOLATED ANNUAL MAINTENANCE DATA

DATA ITEM	SERIES		
	2200	2400	2600
Fleet Size (cars)	144	194	250
Number of Failures	6,984	9,234	8,594
Repair Time (hours)	6,192	6,402	5,688
Number of Inspections	1,022	1,242	1,500
Inspection Time (hours)	4,088	4,968	6,000
Number of Maintenance Actions	8,006	10,476	10,094
Total Maintenance Time	10,282	11,368	11,688
Car-Hours Scheduled	349,000	512,000	629,000

EXHIBIT 4-9

FLEET RELIABILITY/MAINTAINABILITY FACTORS

FACTOR	SERIES		
	2200	2400	2600
MTBF (Car-Hrs/Failure)	50	56	73
MTBM (Car-Hrs/Maintenance Action)	44	49	62
MTBI (Car-Hrs/Inspection)	341	412	419
MTTR (Hrs)	0.9	0.7	0.7
MTTM (Hrs)	1.3	1.1	1.2
R_e (Car-Hrs)	11.0	7.8	7.8

4.4.2 Examination of Subsystem Reliability/Maintainability

The evaluation of railcar performance has also been conducted by investigating the contribution of major subsystems to overall car reliability and maintainability. (See Appendix D for detailed calculations.) Exhibit 4-10 presents the distribution of failures among these major subsystems and Exhibit 4-11 shows the corresponding MTBFs. CTA codes for the respective group are also included. Notice that doors/communications account for the highest percentage of unscheduled maintenance actions for both the 2200- and 2600-Series (24 percent and 36 percent respectively). Consequently, this subsystem is the least reliable as indicated by the MTBF values in Exhibit 4-11. For the 2400-Series propulsion motors contribute 27 percent of all unscheduled maintenance actions, making it the subsystem with the highest failure rate. The three worst offenders, in order of severity are as follows:

2200-series:	doors/communications, propulsion, brakes
2400-series:	propulsion, doors/communications, brakes
2600-series:	doors/communications, brakes, propulsion

Car body is not considered in this ranking since this category includes miscellaneous items not directly allocable to a single subsystem. Notice that, generally, the three worst offenders are the same for each series and reflect the results of the UMTA Transit Reliability Information Program (TRIP).

Percent distribution of repair time is shown in Exhibit 4-12 and the mean time to repair each subsystem is presented in Exhibit 4-13. Notice that the mean time to repair the 2200-Series propulsion system is considerably higher than for the 2400- and 2600-Series. Repair times for all other subsystems are similar for all the car series. Expansion of the sample size might provide more insight into differences among the series' subsystems.

EXHIBIT 4-10

FAILURE DISTRIBUTION

SUBSYSTEM	CODE	% OF UNSCHEDULED MAINTENANCE ACTIONS		
		2200-Series	2400-Series	2600-Series
Propulsion	1000	18	27	12
Car Body	2000	22	18	18
Brakes	3000	14	18	14
Doors/Communications	4000	24	21	36
HVAC	5000	10	4	8
Trucks	6000	2	1	3
ATC	9000	10	11	9

EXHIBIT 4-11

SUBSYSTEM RELIABILITY SUMMARY

SUBSYSTEM	CODE	MEAN TIME BETWEEN FAILURE (MTBF)*		
		2200-Series	2400-Series	2600-Series
Propulsion	1000	275	216	529
Car Body	2000	216	330	373
Brakes	3000	356	322	479
Doors/Communications	4000	205	275	190
HVAC	5000	485	1,467	839
Trucks	6000	2,017	4,414	2,516
ATC	9000	466	507	774

* In hours

SOURCE: See Appendix D for calculations.

EXHIBIT 4-12

DISTRIBUTION OF REPAIR TIME

SUBSYSTEM	CODE	% OF TOTAL REPAIR TIME		
		2200-Series	2400-Series	2600-Series
Propulsion	1000	37	28	10
Car Body	2000	13	15	20
Brakes	3000	13	21	22
Doors/Communications	4000	19	15	28
HVAC	5000	7	4	7
Trucks	6000	3	4	2
ATC	9000	8	13	11

EXHIBIT 4-13

SUBSYSTEM MAINTAINABILITY SUMMARY

SUBSYSTEM	CODE	MEAN TIME TO REPAIR (MTTR)*		
		2200-Series	2400-Series	2600-Series
Propulsion	1000	1.9	0.7	0.6
Car Body	2000	0.5	0.6	0.7
Brakes	3000	0.8	0.8	1.0
Doors/Communications	4000	0.7	0.5	0.5
HVAC	5000	0.6	0.7	0.5
Trucks	6000	1.2	1.0	0.6
ATC	9000	0.8	0.7	0.8

* In hours

5.0 FLEET PERFORMANCE AND COST MODELS

Potential benefits from proposed improvements in railcar performance must be quantifiable so that these benefits can be compared with benefits from competing alternatives. This section presents a procedure which is used to estimate potential economic benefits that can be derived from improvements in CTA railcar reliability and maintainability. The procedure uses mathematical models (and data developed in Section 4) that estimate both potential savings in maintenance cost as well as fleet capital cost savings. Operating cost savings that may result from reduction in service delays have not been addressed since these have been found to be minimal. Detailed development of these models is contained in Ref. 1.

The following paragraphs provide general suggestions as to how the models may be used by CTA in making decisions regarding maintenance and overhaul actions. Section 5.1 presents a more detailed explanation of the basis for both the maintenance cost savings model and the fleet capital cost savings mode. Each of these models has been formulated for the 2200-Series, the 2400-Series, and the 2600-Series railcars based upon CTA data presented in Section 4. These models provide a unique tool for decision-makers because they can be used to estimate cost savings due to changes in railcar reliability and maintainability, a capability which was previously unavailable. Section 5.2 details the calibration of the models and the principles of their use. Section 5.3 presents some suggestions for using the models for testing alternative approaches to improving railcar maintenance and for assessing overhaul decisions.

A major benefit of these models is that they can be used directly to assess the potential effect of improvements in equipment and/or practices and procedures by testing these improvements on selected samples of equipment. For example, if it is believed that a subsystem or component retrofit could be helpful to railcar performance, then a test sample of railcars could be retrofitted. Before and after data on railcar performance for the test sample can be collected and calculations made of the improvements in MTBF and MTTM. An estimate of fleet-wide cost savings due to improved performance can then be made and compared with the costs of retrofitting the entire fleet. In this way CTA management will have a more accurate assessment of the benefit of a specific retrofit program. Similarly, the benefits of modifications to subsystems can be tested in this manner.

With regard to an overhaul program, a proposed overhaul could be performed on a test sample of railcars and, utilizing before and after data, an estimate of the value of a fleet-wide overhaul can be made. Alternative overhaul proposals can be tested as well.

Changes in maintenance practices are another aspect that can be examined in more detail with the models. There are basically two parameters of maintenance practice which can be changed, i.e., the maintenance interval (impacting MTBM) and the maintenance procedures (impacting MTTM). The PATCO experience, as described in Section 3.4.2, indicates that inspection intervals can be changed to achieve an optimum level to balance between the cost of inspections and the cost of unscheduled maintenance. Using data from a test sample of cars in conjunction with the models can provide a basis for deciding whether or not a change in the inspection intervals is cost effective. Similarly, changes in work procedures, which would impact MTTM, can also be evaluated.

5.1 BASIC RATIONALE FOR MODELS

Equipment breakdowns can result in system downtime, lost car hours, higher level of maintenance and, consequently, increased operating and maintenance cost. Equipment breakdowns also result in higher capital costs since transit authorities must make allowances for car unavailability in new car acquisitions. This results not only in higher capital commitment for increased fleet size, but also in the increased cost needed to provide larger maintenance and storage facilities. By reducing railcar failure rates and/or car downtime, operating costs will be reduced through reduced service delays, maintenance costs will drop as a result of lower labor and parts requirement, and fleet capital cost will also be lower because the need for spare cars would have been minimized. Two major areas that are relevant to this study include maintenance and fleet capital cost savings from improved railcar performance.

5.1.1 Maintenance Cost Savings Model

The maintenance cost model estimates both potential labor and spare parts cost savings from improved reliability/maintainability. While labor cost savings derive from reductions in failure rate and/or mean time to repair failed cars, the spare parts cost savings result only from reduced failure rates. Because maintenance costs are incurred from all maintenance actions, the maintenance cost savings model takes account of both service- and non-service-related failures.

The relationship for estimating potential maintenance cost savings based on unscheduled maintenance actions alone has been developed in a recent study (Ref. 1); the relationship is as follows:

$$\Delta C_{um} = N_f \left[K_s \, R_s \left(\frac{P_f + P_r}{1 + P_f} \right) + K_{up} \left(\frac{P_f}{1 + P_f} \right) \right] \tag{5-1}$$

where ΔC_{um} = unscheduled maintenance cost savings.

N_f = total number of unscheduled maintenance actions for fleet during the period under investigation

K_s = unscheduled maintenance labor cost factor. This represents the cost per shop car-hour and is expressed in dollars per car-hour. It is given by C_{ul} / D_s where C_{ul} = total labor cost for all unscheduled maintenance actions and D_s = shop time for unscheduled maintenance actions.

R_s = MTTR = mean time to repair (car-hours) = D_s / N_f

K_{up} = unscheduled maintenance parts cost factor. It relates spare parts cost due to unscheduled maintenance to number of unscheduled maintenance actions and is given by C_{up} / N_f, where C_{up} = cost of spare parts consumed in unscheduled maintenance and N_f is as defined above.

$$p_f = \text{improvement in MTBF} = \frac{\text{change in MTBF}}{\text{initial MTBF}}$$

$$p_r = \text{improvement in MTTR} = \frac{\text{change in MTTR}}{\text{initial MTTR}}$$

By reformatting equation (5-1) to reflect both scheduled and unscheduled maintenance actions, total maintenance cost savings is given by:

$$\Delta C_m = N_m \left[K_m R_m \left(\frac{p_m + p_t}{1 + p_m} \right) + K_p \left(\frac{p_m}{1 + p_m} \right) \right] = C_{ml} \left(\frac{p_m + p_t}{1 + p_m} \right) + C_{mp} \left(\frac{p_m}{1 + p_m} \right) \quad (5\text{-}2)$$

where ΔCm = total maintenance cost savings (unscheduled and scheduled)

C_{ml} = total labor cost for unscheduled and scheduled maintenance

C_{mp} = total spare parts cost for unscheduled and scheduled maintenance

N_m = total number of maintenance actions (scheduled and unscheduled)

K_m = total maintenance labor cost factor = C_{ml} / D_m, where D_m = shop time for both unscheduled and scheduled maintenance actions.

R_m = MTTM = mean time to maintain = D_m / N_m

K_p = total spare parts cost factor for scheduled and unscheduled maintenance = C_{mp} / N_m

$$p_m = \text{improvement in MTBM} = \frac{\text{change in MTBM}}{\text{initial MTBM}}$$

$$p_t = \text{improvement in MTTM} = \frac{\text{change in MTTM}}{\text{initial MTTM}}$$

5.1.2 Fleet Capital Cost Savings Model

Savings in fleet capital cost are reflected in the reduction of the spare car requirement realized as a result of improved car reliability and maintainability. Car-hours are lost due to failures occurring in service as well as failures detected when the car is in the shop for other maintenance. Hence, the fleet cost model also considers both service- and non-service-related incidents.

The reduction in the spare car requirement, and consequently fleet cost, is directly related to the reduction in car downtime realized through improvements in car performance. The car-hours of downtime saved can be translated into the number of cars saved through the following relationship, the details of which have been explained in Ref. 1.

$$\Delta N_c = N_o \left(\frac{p_m + p_t}{1 + p} \right) \frac{R_e}{L} \tag{5-3}$$

where ΔN_c = number of cars that can be saved

N_o = number of cars required for service

L = mean time between maintenance actions

R_e = mean time to restore

p_m, p_t are as defined above

5.2 CALIBRATING AND USING THE MODELS

The relationships for maintenance cost savings and fleet capital cost reduction (number of cars saved) must be calibrated for each transit authority before they can

be used to investigate benefits from performance improvements. Results of the data reduction efforts discussed in Section 4.3 have been used to calibrate these models for CTA (detailed calibration procedure is shown in Appendix E). While expressing cost directly as a function of car reliability/maintainability factors, it should be pointed out that the results of this analysis are only indicative of the general level of savings that is achievable through improved reliability and maintainability.

5.2.1 Potential Maintenance Cost Reduction

Maintenance cost savings for the three series are obtained by the following calibrated equations.

<u>2200-Series</u>

$$\Delta C_m = 1,100,000 \left(\frac{p_m + p_t}{1 + p_m} \right) + 1,700,000 \left(\frac{p_m}{1 + p_m} \right) \qquad (5\text{-}4)$$

<u>2400-Series</u>

$$\Delta C_m = 1,900,000 \left(\frac{p_m + p_t}{1 + p_m} \right) + 2,000,000 \left(\frac{p_m}{1 + p_m} \right) \qquad (5\text{-}5)$$

<u>2600-Series</u>

$$\Delta C_m = 2,000,000 \left(\frac{p_m + p_t}{1 + p_m} \right) + 1,100,000 \left(\frac{p_m}{1 + p_m} \right) \qquad (5\text{-}6)$$

Recognizing that p_m = improvement in MTBM and p_t = improvement in MTTM, potential maintenance cost savings at any level of reliability/maintainability improvements can be examined by varying p_m and/or p_t in each of the above equations. A sensitivity analysis has been conducted by calculating potential cost savings for each series for varying levels of p_m and p_t. For each car series, cost savings are calculated first by keeping mean time between maintenance constant at a known level and varying the mean time to maintain. A second analysis is then conducted by holding mean time to maintain constant and varying the mean time between maintenance. Results of these analyses are presented in Tables E-1 through E-6 in Appendix E.

To facilitate the use of the models, the calculated results can also be presented as a set of easy-to-use graphs which can be employed without reference

to the mathematical formulation once the defining parameters have been established. Exhibits 5-1 through 5-6 present six sets of graphs relating improvements in MTBM and MTTM with associated potential savings in maintenance cost. Two sets of graphs have been plotted for each car series. One set illustrates variations in the MTTM at fixed levels of MTBM. The other illustrates variations in MTBM for fixed levels of MTTM.

The maintenance cost/equipment performance relationships for the 2200-Series are used to demonstrate the use of these models. Shown in Exhibits 5-1 and 5-2, the relationships have been obtained by varying p_m (the improvement in MTBM) and p_t (the improvement in MTTM) in equation (5-4) above. The vertical axes represent the potential annual maintenance cost savings (dollars), while the horizontal axes represent the improvements in MTTM (Exhibit 5-1) and MTBM (Exhibit 5-2) expressed as percentages of their respective values prior to improvements. Either of these two sets of graphs can be used to analyze potential maintenance cost savings for improvements in reliability or maintainability of the 2200-Series of cars.

Consider Exhibit 5-1 which plots a set of linear relationships between cost savings and changes in MTTM for various levels of MTBM. The set of lines are plotted only in the positive quadrant representing improvements in MTTM (reduction in MTTM) and improvements in MTBM (increase in MTBM). Potential cost savings can be realized by either or both of these improvements by entering this chart with the percent improvement in MTBM and/or MTTM and reading the corresponding cost savings from the vertical axis. Notice that the maximum improvement in MTTM will correspond to the hypothetical case where it takes zero time to maintain a car, that is $p_t = 100$ percent. On the other hand, maximum improvement in MTBM will occur when the car operates perpetually without the need for maintenance, that is, $p_m = \infty$. For purposes of this analysis, the set of graphs are, however, bounded between $p_m = 100$ percent (that is, doubling the MTBM) and $p_t = 100$ percent (zero time to maintain). Maximum annual maintenance cost savings for this hypothetical case is about \$2 million and is given by the topmost line in Exhibit 5-1. For zero MTTM reduction ($p_t = 0$ percent) and a 100 percent increase in MTBM (that is $p_m = 100$ percent), an annual savings of about \$1.4 million (or half of estimated annual maintenance cost for the 2200-Series) could be obtained. Note that a

EXHIBIT 5-1

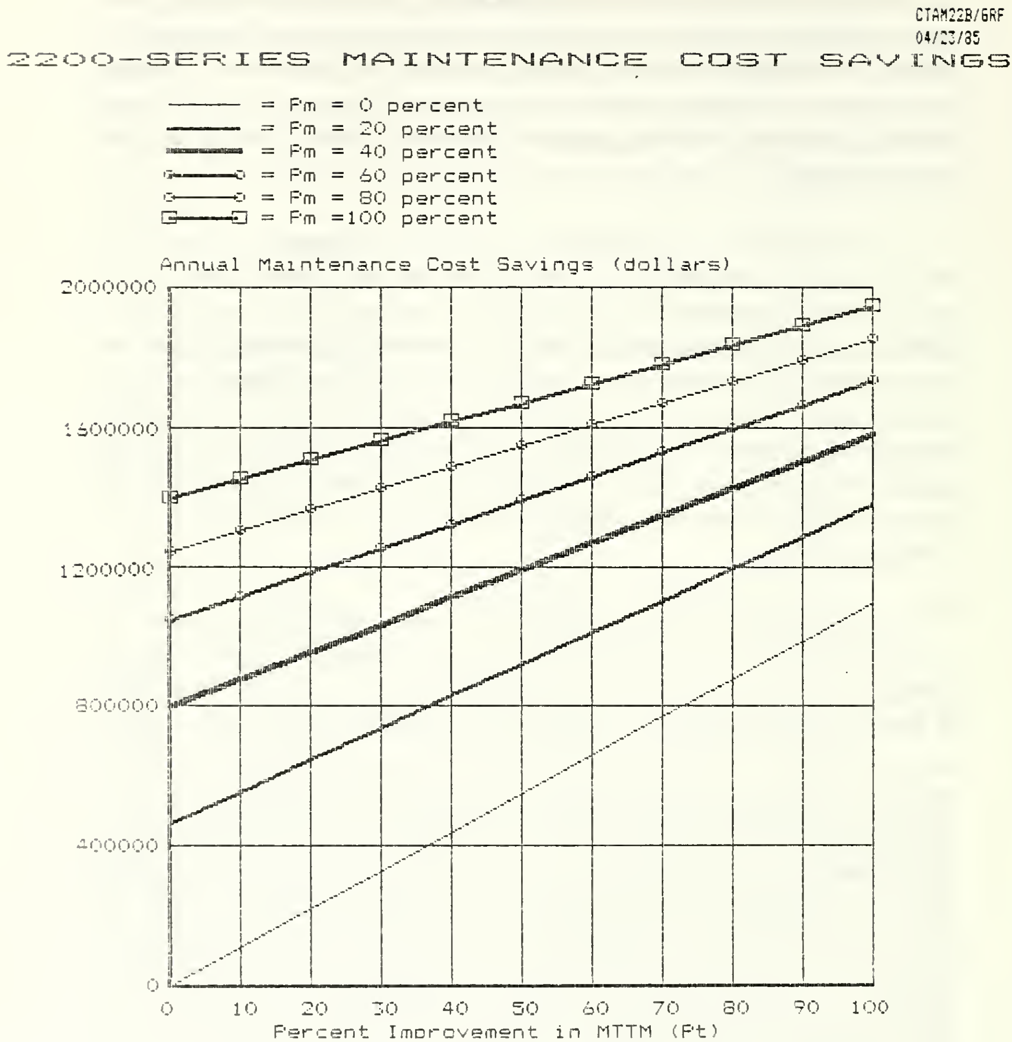

CTAM22B/GRF
04/23/85
2200-SERIES MAINTENANCE COST SAVINGS
= Fm = 0 percent
= Fm = 20 percent
= Fm = 40 percent
= Fm = 60 percent
= Fm = 80 percent
= Fm =100 percent
Annual Maintenance Cost Savings (dollars)
2000000
1600000
1200000
800000
400000
0
0
10
20
30
40
50
60
70
80
90
100
Percent Improvement in MTTM (Pt)

EXHIBIT 5-2

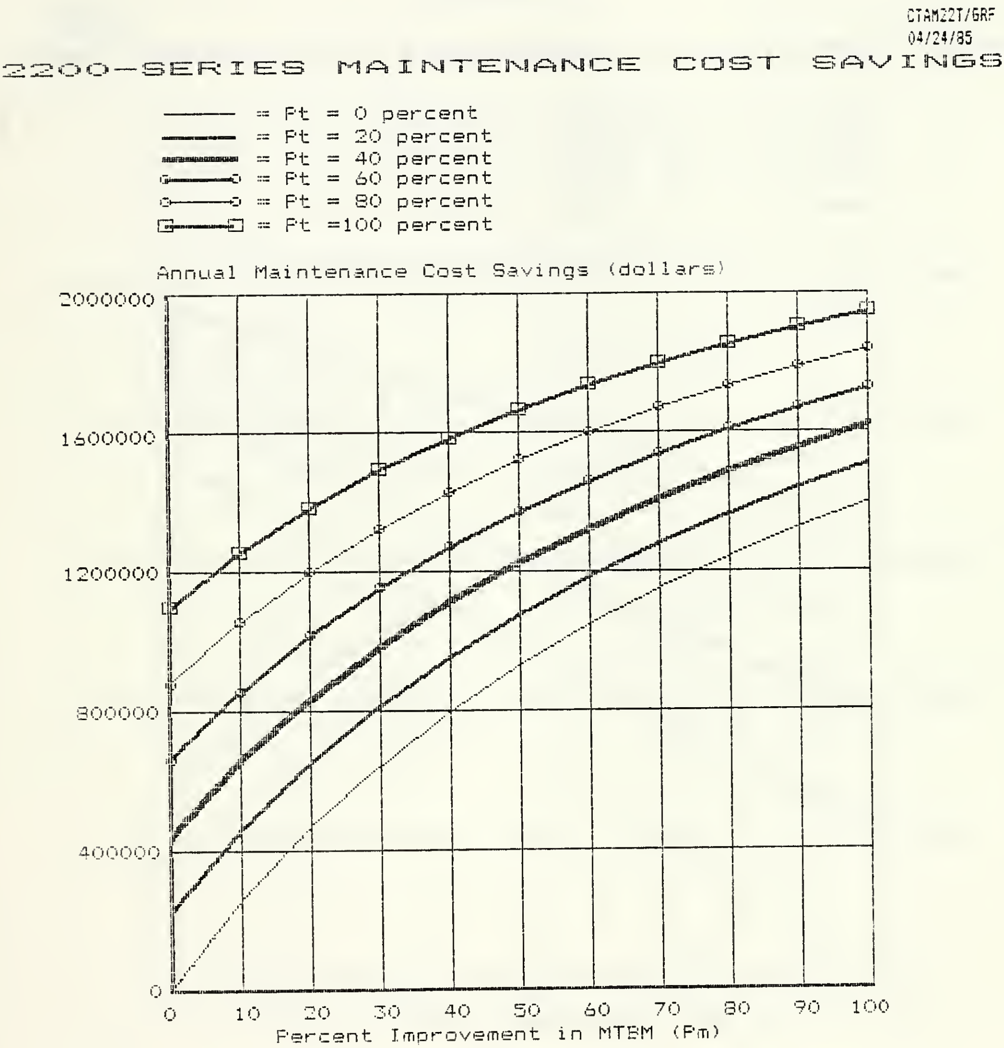
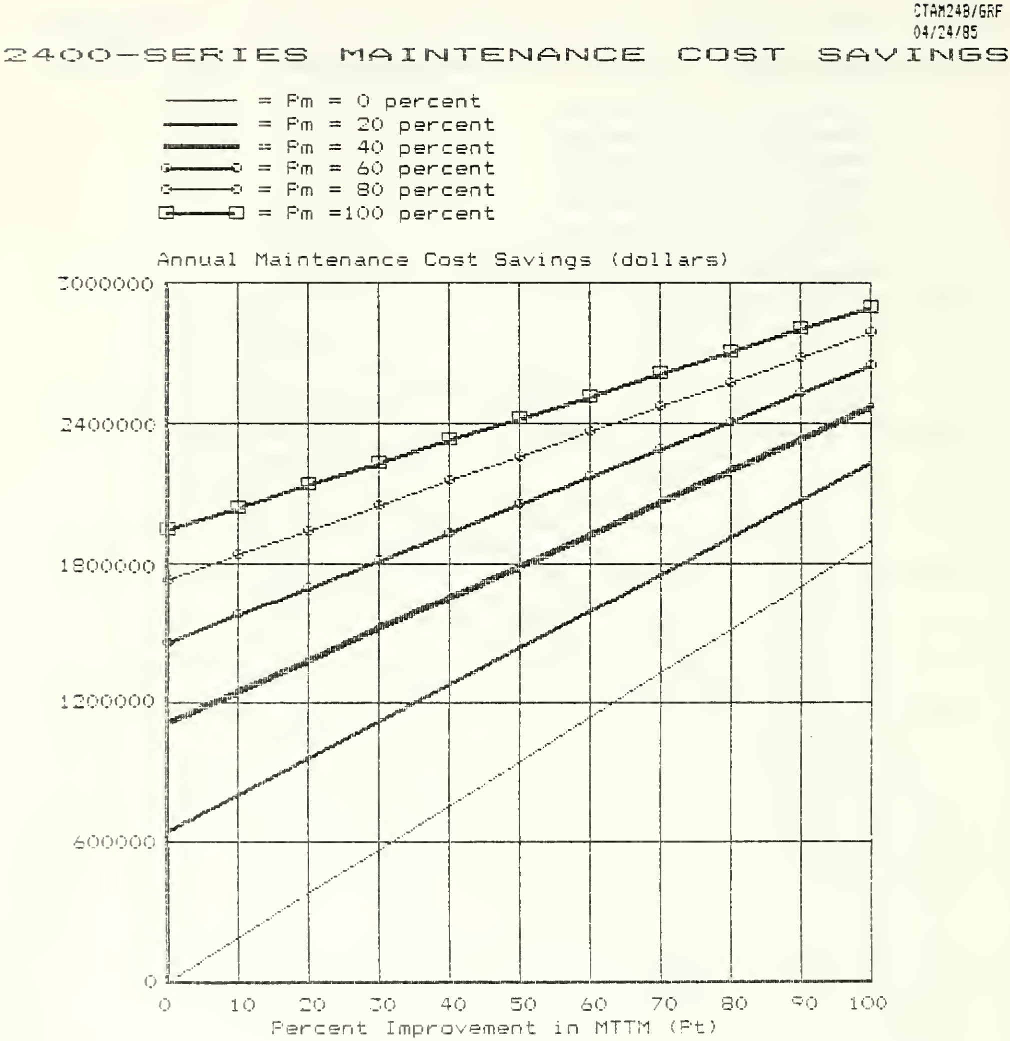
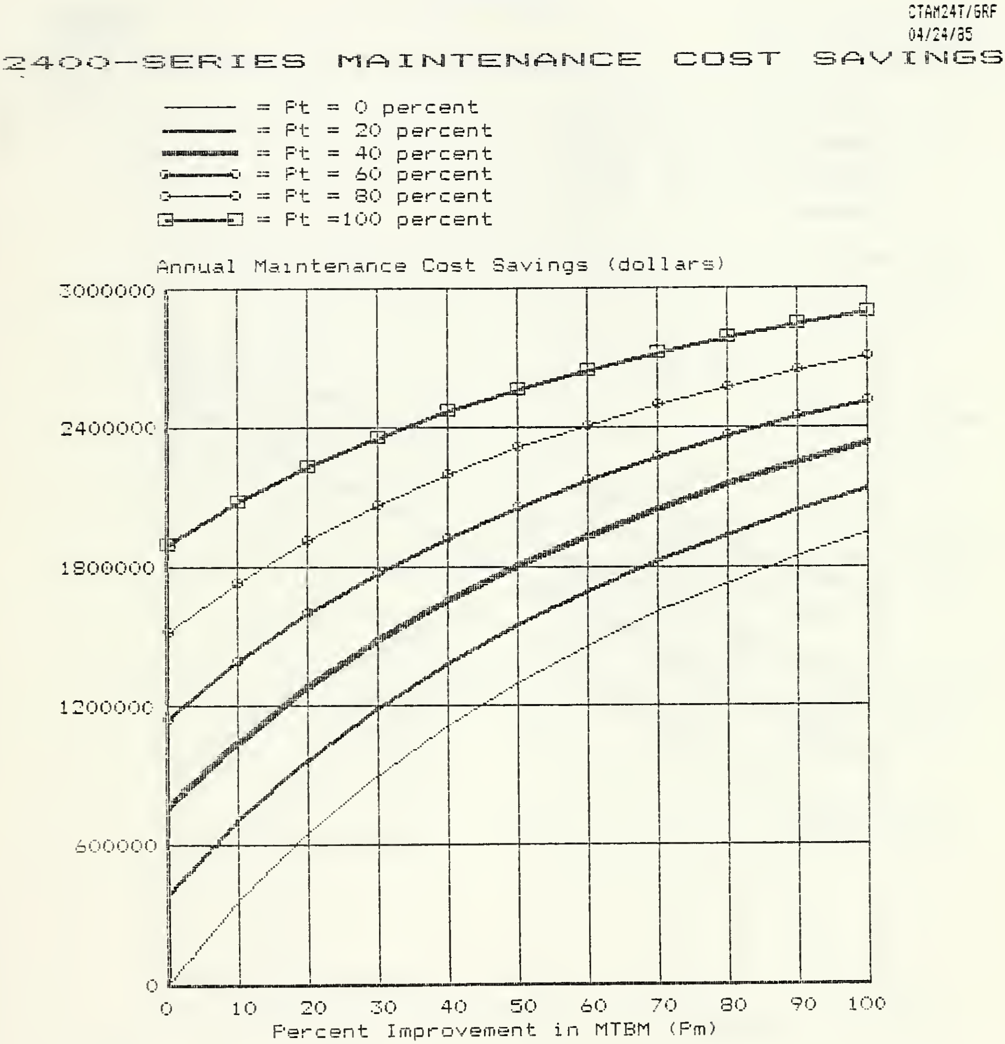

CTAM22T/GRF
04/24/85
2200-SERIES MAINTENANCE COST SAVINGS
= Pt = 0 percent
= Pt = 20 percent
= Pt = 40 percent
= Pt = 60 percent
= Pt = 80 percent
= Pt =100 percent
Annual Maintenance Cost Savings (dollars)
2000000
1600000
1200000
800000
400000
0
0
10
20
30
40
50
60
70
80
90
100
Percent Improvement in MTBM (Pm)

EXHIBIT 5-3



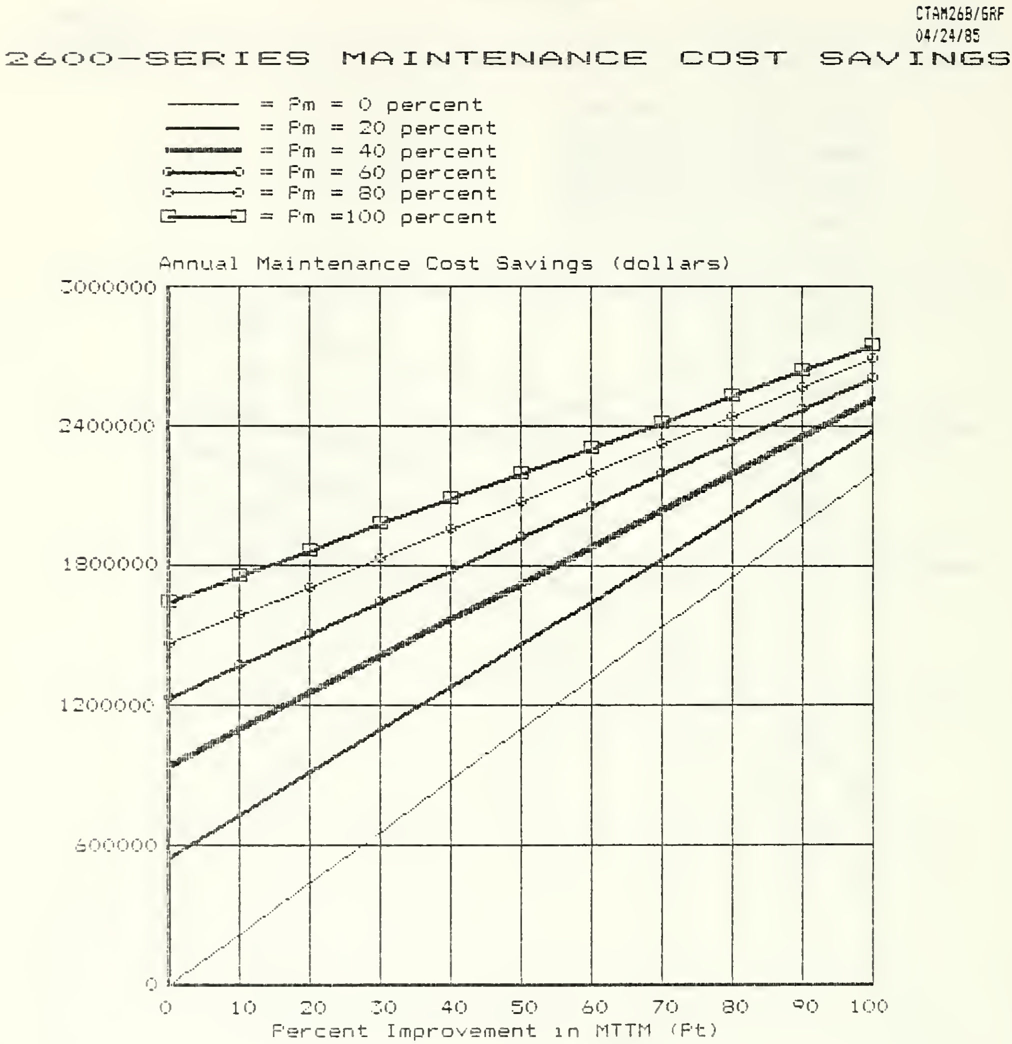
CTAM24B/GRF
04/24/85
2400-SERIES MAINTENANCE COST SAVINGS
= Pm = 0 percent
= Pm = 20 percent
= Pm = 40 percent
= Pm = 60 percent
= Pm = 80 percent
= Pm =100 percent
Annual Maintenance Cost Savings (dollars)
3000000
2400000
1800000
1200000
600000
0
0
10
20
30
40
50
60
70
80
90
100
Percent Improvement in MTTM (Pt)

EXHIBIT 5-4



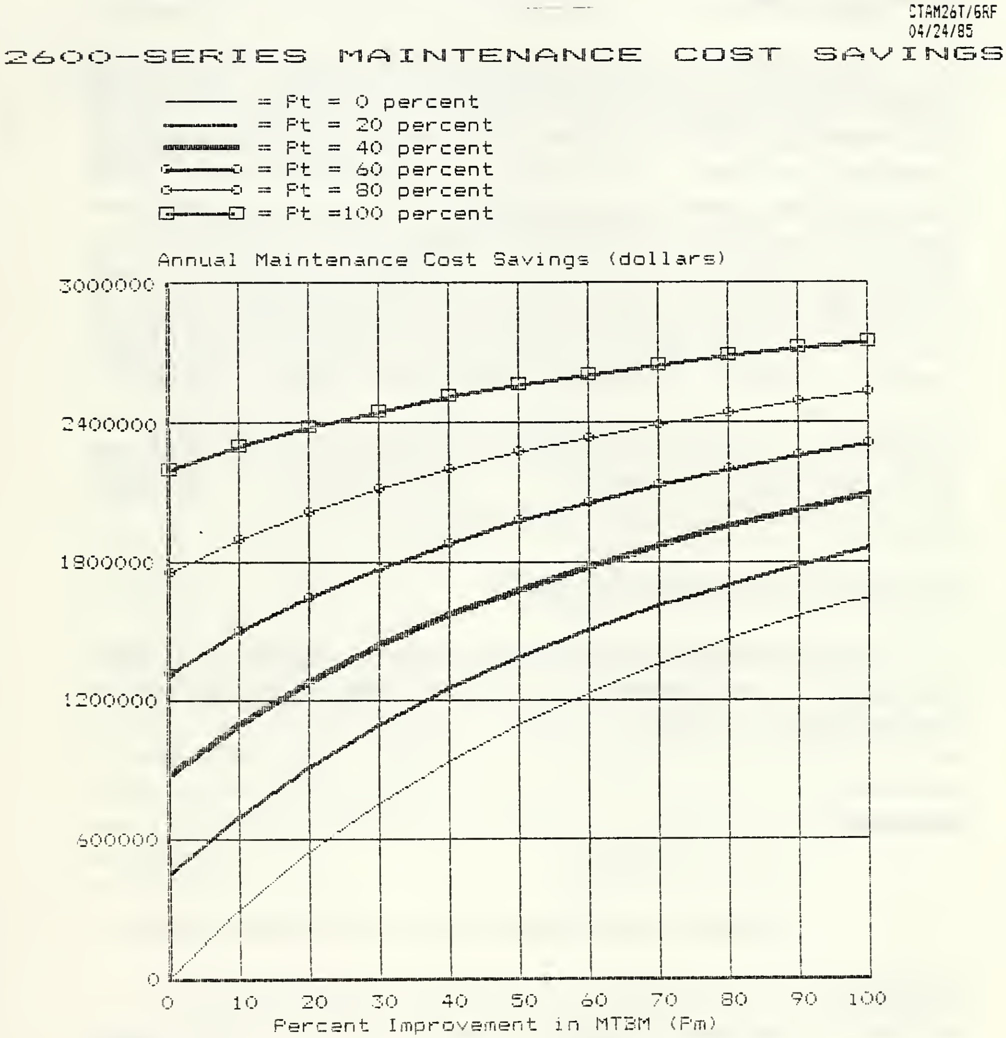
CTAM24T/GRF
04/24/85
2400-SERIES MAINTENANCE COST SAVINGS
= Pt = 0 percent
= Pt = 20 percent
= Pt = 40 percent
= Pt = 60 percent
= Pt = 80 percent
= Pt =100 percent
Annual Maintenance Cost Savings (dollars)
3000000
2400000
1800000
1200000
600000
0
0
10
20
30
40
50
60
70
80
90
100
Percent Improvement in MTBM (Pm)

EXHIBIT 5-5



CTAM26B/GRF
04/24/85
2600-SERIES MAINTENANCE COST SAVINGS
= Pm = 0 percent
= Pm = 20 percent
= Pm = 40 percent
= Pm = 60 percent
= Pm = 80 percent
= Pm =100 percent
Annual Maintenance Cost Savings (dollars)
3000000
2400000
1800000
1200000
600000
0
0
10
20
30
40
50
60
70
80
90
100
Percent Improvement in MTTM (Pt)

EXHIBIT 5-6


CTAM26T/GRF
04/24/85
2600-SERIES MAINTENANCE COST SAVINGS
= Pt = 0 percent
= Pt = 20 percent
= Pt = 40 percent
= Pt = 60 percent
= Pt = 80 percent
= Pt =100 percent
Annual Maintenance Cost Savings (dollars)
3000000
2400000
1800000
1200000
600000
0
0
10
20
30
40
50
60
70
80
90
100
Percent Improvement in MTBM (Pm)

100-percent increase in MTBM is equivalent to a 50-percent reduction in number of maintenance actions.

It is important to recognize that the horizontal axis (change in MTTM) can be extended to the left (negative values) to represent increases in MTTM. Notice also that improving the MTBM can allow the MTTM to increase substantially without any maintenance cost penalty. For example, a 40 percent improvement in MTBM (p_m = 40 percent), without a change in MTTM has potential for saving $800,000 in annual maintenance cost on the 2200-Series. Extending the p_m = 40 percent line to intersect the horizontal axis, indicates that a 40 percent improvement in MTBM would permit the MTTM to increase by up to twice the original value before costs are increased. In other words, by doubling the MTTM (to allow for more thorough inspection and repair of the 2200-series cars) and thereby realizing a 40% improvement in MTBM, the overall annual maintenance cost will remain unchanged. A net maintenance cost savings can be realized if 40% improvement in MTBM is achieved at less than double the current MTTM. Detailed implications of these results relative to CTA maintenance program are discussed in a later section.

5.2.2 Potential Fleet Capital Cost Reduction

Potential fleet capital cost savings have been expressed in terms of number of cars that can be saved in Equation (5-3). Pertinent calibrated equations for each series are presented as follows:

<u>2200-Series</u>

$$\Delta N_c = 28 \frac{p_m + p_t}{1 + p_m} \qquad (5\text{-}7)$$

<u>2400-Series</u>

$$\Delta N_c = 26 \frac{p_m + p_t}{1 + p_m} \qquad (5\text{-}8)$$

<u>2600-Series</u>

$$\Delta N_c = 24 \frac{p_m + p_t}{1 + p_m} \qquad (5\text{-}9)$$

Using the same approach of separately varying one parameter while keeping the other constant, potential fleet size reduction at various levels of reliability/ maintainability improvements can be determined for each car series. The calculated results of these analyses are also presented in Appendix E, Tables E-7 through E-12. It should be noted that the number of cars that can be saved (equations 5-7 through 5-9) are given as a fraction of the required number of spares estimated for each series.

The calculated results are presented graphically in Exhibits 5-7 through 5-12 for the 2200-, 2400-, and 2600-Series. Notice that the maximum number of cars that can be saved converges to the number of spares estimated for each series in Appendix C. For a hypothetical 100 percent improvement in MTTM (that is, zero maintenance time), there will be, theoretically, no need for spares.

The graphs for the 2200-Series (Exhibits 5-7 and 5-8) are also used to demonstrate the application of the models. If the percent improvements in MTTM and MTBM are known, these values can be used to enter Exhibits 5-7 or 5-8 in order to determine the number of 2200-Series cars that can be saved as a result of the improvements. These cars will be in addition to the ten cars calculated as excess on the basis of current spare allowance (see Appendix B). For example, consider a change in maintenance practice and/or subsystem modification that results in a modest 20 percent improvement in MTTM only. Exhibits 5-7 or 5-8 can be entered with $p_t = 20$ percent, $p_m = 0$ percent to obtain a savings of six 2200-Series cars. This means that the spare requirement can be reduced to 20 cars, down from 26 cars initially estimated for the series prior to this improvement. Hence, total excess cars of the 2200-Series will be 18 cars based on the estimate of fleet requirement for this series.

5.3 IMPLICATIONS RELATIVE TO CTA MAINTENANCE PROGRAM

The following paragraphs demonstrate the implications of results from the models relative to the CTA maintenance program. It should be kept in mind that the data sample which was used to develop the model was limited and that it would be desirable to expand on this data base before performing any extensive analyses with the models. However, the results which have been obtained can be considered as indicative of the existing situation.

EXHIBIT 5-7

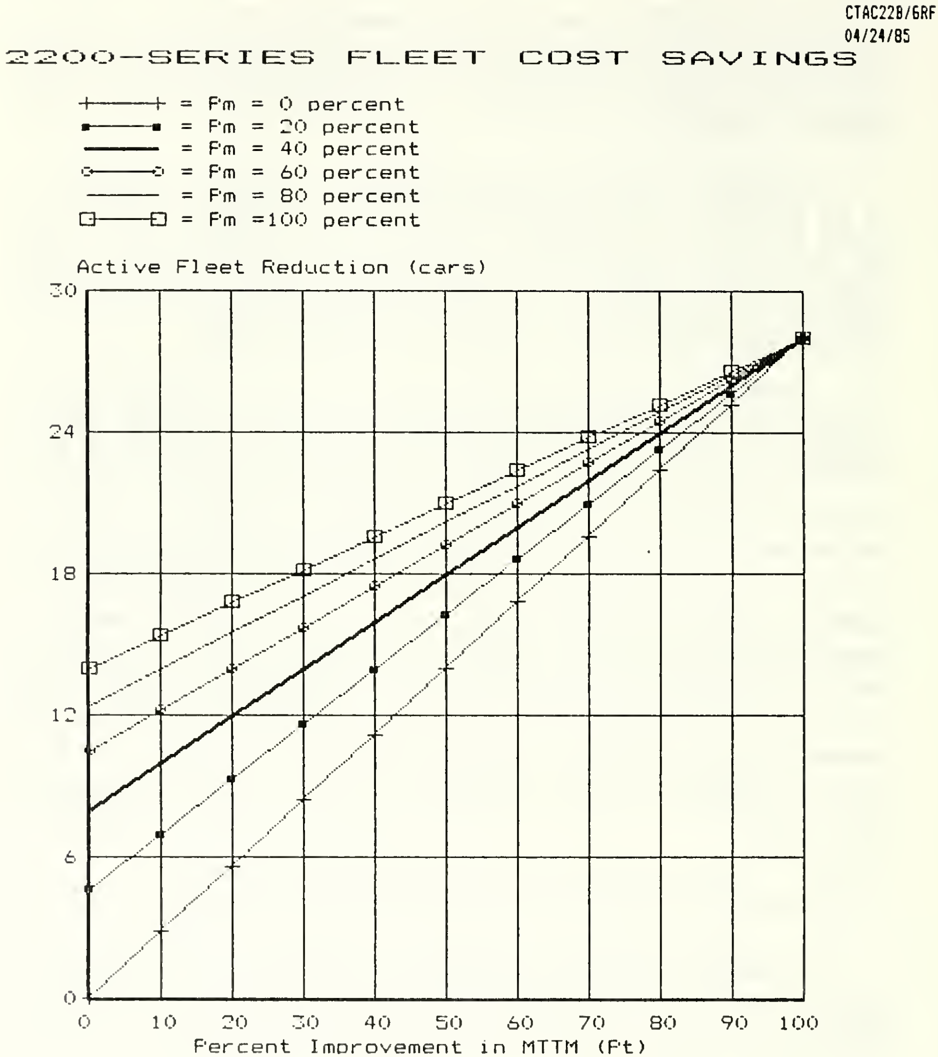

CTAC22B/GRF
04/24/85
2200-SERIES FLEET COST SAVINGS
= Pm = 0 percent
= Pm = 20 percent
= Pm = 40 percent
= Pm = 60 percent
= Pm = 80 percent
= Pm =100 percent
Active Fleet Reduction (cars)
30
24
18
12
6
0
0
10
20
30
40
50
60
70
80
90
100
Percent Improvement in MTTM (Pt)

EXHIBIT 5-8

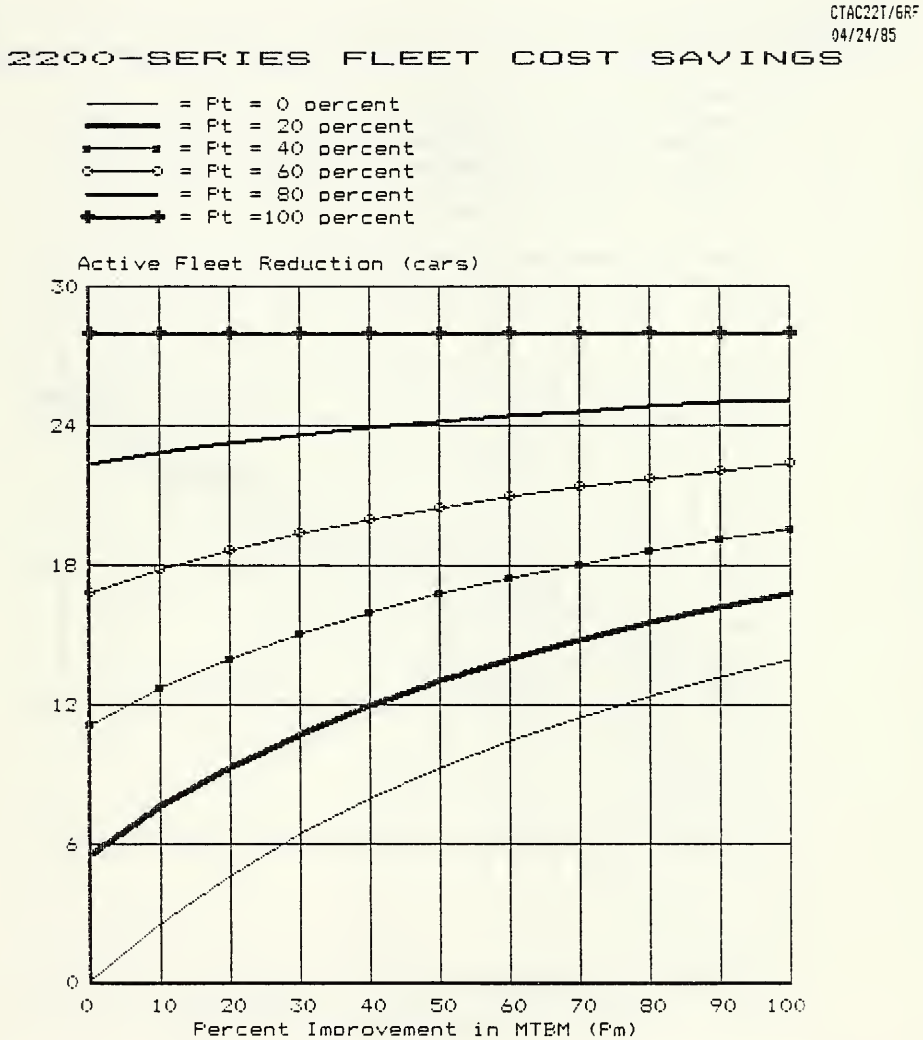

CTAC22T/GRF
04/24/85
2200-SERIES FLEET COST SAVINGS
= Pt = 0 percent
= Pt = 20 percent
= Pt = 40 percent
= Pt = 60 percent
= Pt = 80 percent
= Pt =100 percent
Active Fleet Reduction (cars)
30
24
18
12
6
0
0
10
20
30
40
50
60
70
80
90
100
Percent Improvement in MTBM (Pm)

EXHIBIT 5-9

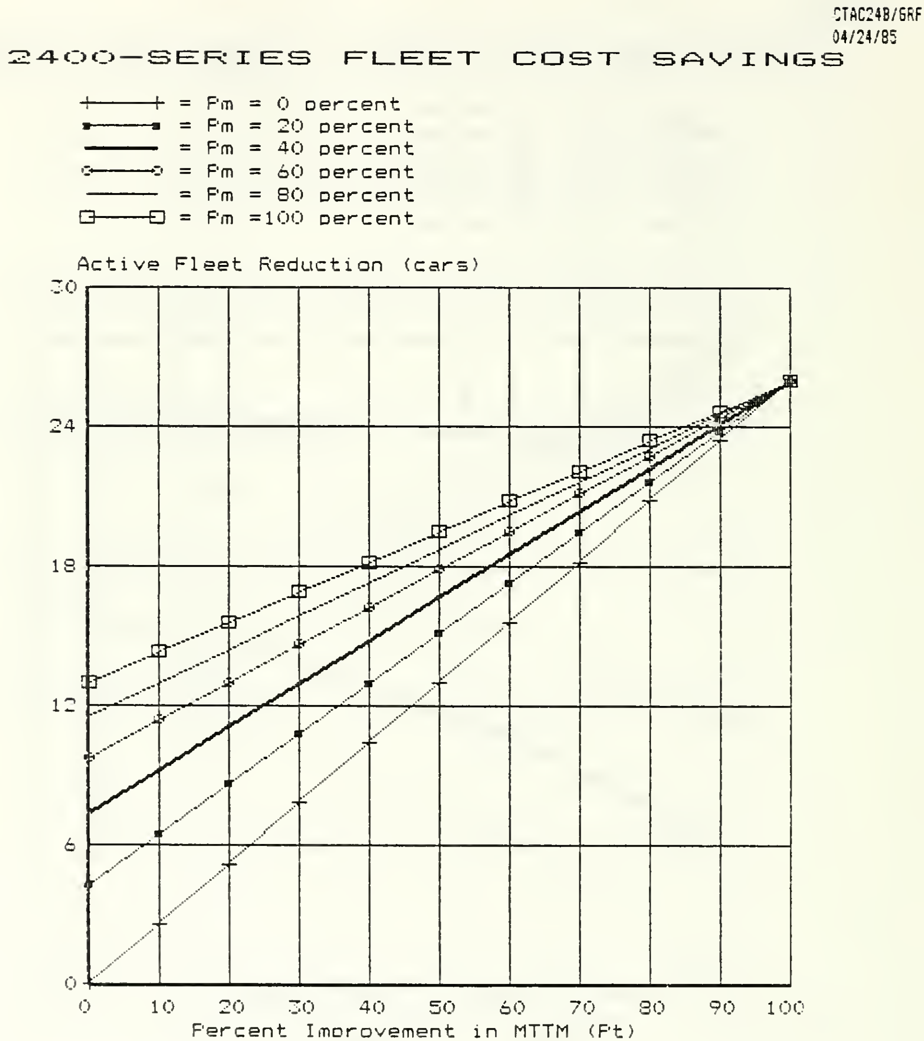
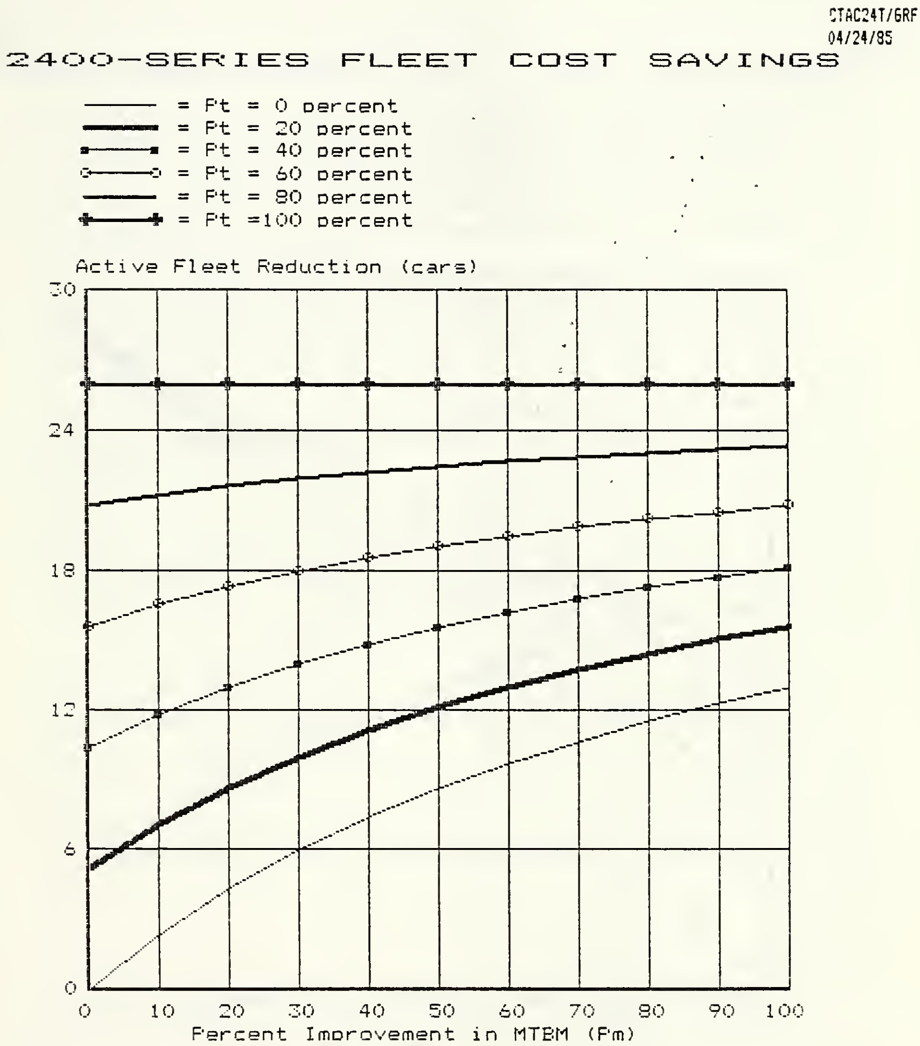

CTAC24B/GRF
04/24/85
2400-SERIES FLEET COST SAVINGS
= Fm = 0 percent
= Fm = 20 percent
= Fm = 40 percent
= Fm = 60 percent
= Fm = 80 percent
= Fm =100 percent
Active Fleet Reduction (cars)
30
24
18
12
6
0
0
10
20
30
40
50
60
70
80
90
100
Percent Improvement in MTTM (Pt)

EXHIBIT 5–10



CTAC24T/GRF
04/24/85
2400-SERIES FLEET COST SAVINGS
= Pt = 0 percent
= Pt = 20 percent
= Pt = 40 percent
= Pt = 60 percent
= Pt = 80 percent
= Pt =100 percent
Active Fleet Reduction (cars)
30
24
18
12
6
0
0
10
20
30
40
50
60
70
80
90
100
Percent Improvement in MTBM (Pm)

EXHIBIT 5-11

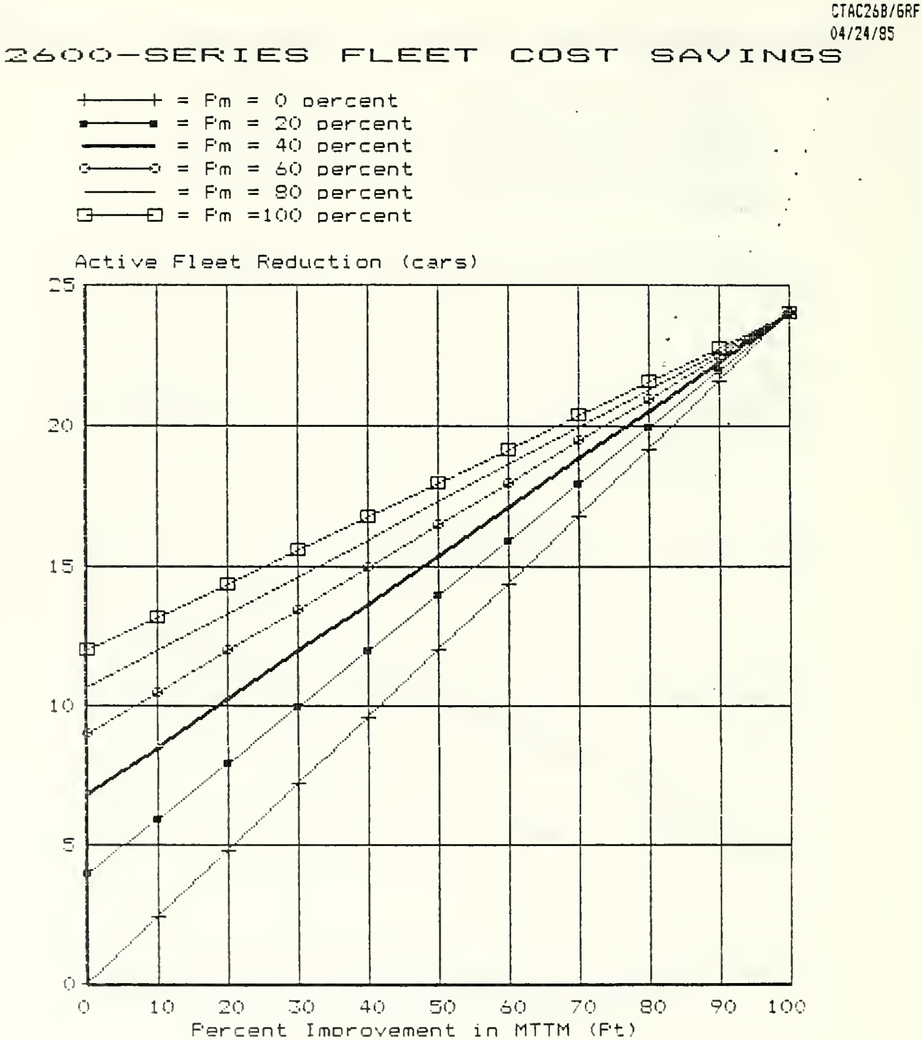
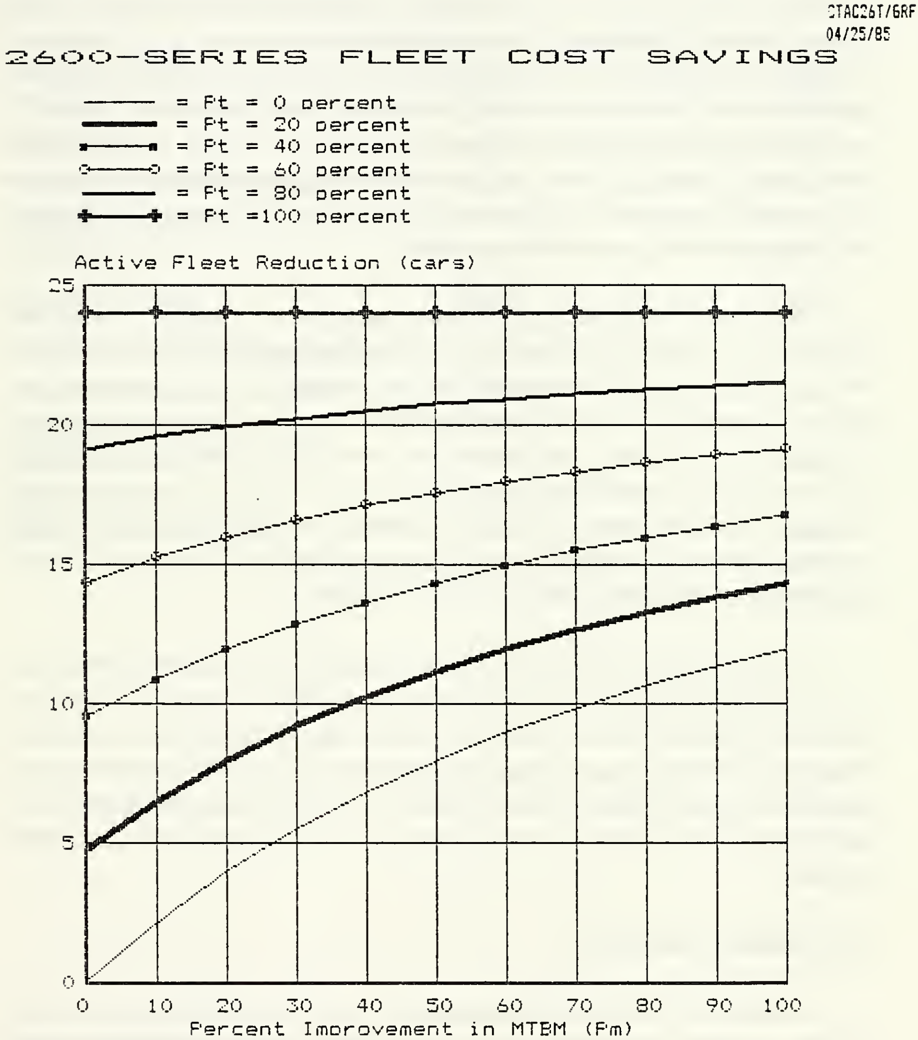

CTAC26B/GRF
04/24/85
2600-SERIES FLEET COST SAVINGS
= Pm = 0 percent
= Pm = 20 percent
= Pm = 40 percent
= Pm = 60 percent
= Pm = 80 percent
= Pm =100 percent
Active Fleet Reduction (cars)
25
20
15
10
5
0
0
10
20
30
40
50
60
70
80
90
100
Percent Improvement in MTTM (Pt)

EXHIBIT 5-12



CTAC26T/6RF
04/25/85
2600-SERIES FLEET COST SAVINGS
= Pt = 0 percent
= Pt = 20 percent
= Pt = 40 percent
= Pt = 60 percent
= Pt = 80 percent
= Pt =100 percent
Active Fleet Reduction (cars)
25
20
15
10
5
0
0
10
20
30
40
50
60
70
80
90
100
Percent Improvement in MTBM (Pm)

5.3.1 Unit Maintenance Cost Factors

Unit maintenance cost factors for each car series have been estimated in Appendix E. These factors, which are direct derivatives of the development of the models, provide an indication of the cost-effectiveness of current CTA maintenance practice. The maintenance labor cost factor, k_m relates labor cost for scheduled and unscheduled maintenance to total maintenance time for each car series. It represents the maintenance labor cost per car-hour of maintenance. The spare parts cost factor k_p relates the parts cost for scheduled and unscheduled maintenance to the number of maintenance actions experienced by each car series. It represents the average parts cost per maintenance action.

Exhibit 5-13 compares the maintenance experience for each car series with related unit maintenance cost factors for the data and period which was examined. Notice that labor cost per maintenance car-hour is highest for the 2600-Series cars, followed by the 2400-Series, and then 2200-Series. This is not completely surprising in view of the following: the newer cars have more sophisticated electronic components which must nevertheless operate in a very harsh transit environment (i.e., electrical disturbances, vibrations, temperature variations, dust and dirt, etc.) and which require an additional level of troubleshooting time. In addition, the new cars have been experiencing excessive burn-in problems.

From the point of view of parts costs, however, the older 2200-Series cars have the highest average parts cost per maintenance action. This can be partially explained by the fact that the parts on the older cars are worn and that there are likely to be more worn parts, many of which are large and/or expensive and/or unavailable except through a special order; on the other hand, the parts on the newer cars are still in their early life, should be readily available and should be less expensive.

5.3.2 Rebuild Versus Replace

As with most transit authorities, one of the primary considerations of CTA in adopting a maintenance strategy concerns the choice between rehabilitating and replacing cars. The primary impetus for considering the rebuilding or replacing of

EXHIBIT 5-13

COMPARATIVE MAINTENANCE DATA AND MAINTENANCE COSTS

DATA ITEM	SERIES		
	2200	2400	2600
Fleet Size (cars)	144	194	250
Number of Maintenance Actions	8,006	10,476	10,094
Average Number of Maintenance Actions per Car	56	54	40
Number of Failures	6,984	9,234	8,594
Average Number of Failures per Car	49	48	34
Mean Time to Maintain (hours)	1.3	1.1	1.2
Maintenance Labor Cost Factor ($ per car-hour)	107	167	188
Spare Parts Cost Factor ($ per maintenance action)	212	191	109

an aging fleet is deteriorating reliability accompanied by increasing maintenance costs and by worsening fleet availability. This issue has been raised at CTA in connection with some of the fleet.

A preliminary evaluation of the rebuild/replace decision must be made to determine if rebuilding is an option for remedying acute reliability and maintainability problems. Rebuilding existing cars may not be considered an option for a number of reasons. First, new cars may be preferred if the current fleet, even at 100 percent availability, cannot meet peak service demand. Second, existing cars may require such extensive work that rebuilding cannot be considered. This was found to be the case with the 2000-Series. Third, rebuilding may not be attractive because of limitations in available facilities and manpower. Space for rebuilding and the storage of replacement or rebuilt parts may not be available on the transit authority property. Also, available manpower may be insufficient for the requirements of a rebuild program. The problem of facilities and manpower for a rebuild program as it relates to CTA was investigated by CTA Engineering Department and is also addressed in detail in Section 6 of this report. The fourth major consideration in deciding if rebuilding is an option is the availability of funds. Budget restrictions may even rule out both new cars and rebuilding and the authority may be compelled to rely on existing cars. This issue and its impact relative to CTA program was addressed in Section 3.

If an examination of the above considerations indicates that rebuilding is a viable option, then a more comprehensive financial analysis should be made to estimate the value to the property of each alternative—rebuild or buy new. Facility, rebuilding, logistics supply, and all overhead costs related to a rebuild program must be estimated. Since new railcars are regularly being ordered and delivered somewhere in this country, the cost of new cars can be easily estimated.

Estimates of rebuild costs for specific railcar series are included in CTA's report on rapid transit car rehabilitation and purchase plan. To complete the rebuild/replace analysis, it is necessary to estimate the expected life of a rebuilt car and that of the new car in order to amortize the costs discussed above. This economic analysis should also include the required maintenance costs for both alternatives. The cost/performance model discussed in this study can be used as part of this life cycle cost analysis to assist in making decisions between rebuilding and replacing CTA cars. The process involves the comparision of potential net

benefits that can be realized by improving the performance and extending the life of an existing car against the net benefits from buying new and possibly more reliable equipment. To do this, each car series would have to be analyzed on the basis of its current reliability and maintainability.

The value of the models in this type of decision is the ability to perform "what if" analyses quickly and inexpensively. For example, estimates of the expected improvement in reliability and maintainability for a rebuilt fleet can be made in conjunction with the maintenance staff. The models for that fleet can then be used to generate estimates of maintenance cost savings. These cost savings can be compared to the rebuild costs to determine the value of the rebuild. Additional analyses can be made to the value of a new car purchase over time as compared to the value of a rebuild. (A detailed explanation of the procedure and the necessary assumptions is presented in Ref. 1 for a hypothetical situation.)

5.3.3 Equipment Retrofit

On the basis of the data which was examined, doors/communications, propulsion, and brakes were identified as the worst offenders for each of the three series studied. For example, the data shows that the propulsion subsystem was the least reliable for the 2400-Series (see Exhibit 4-10). It was estimated to account for about 27 percent of all unscheduled maintenance actions, a significantly high cause of failure for this particular fleet. Two things can be done to improve the reliability of this subsystem and consequently the overall performance of the 2400-Series cars. First, CTA may opt for a retrofit program that will reflect changes in the subsystem design; this is not a particularly attractive alternative for the propulsion system in view of the cost of such a program although it may be appropriate for other vehicle subsystems. A second option, which may be more feasible, could involve changes in the existing maintenance practice for this subsystem.

If it is believed that a retrofit of a subsystem or a component would be helpful but the available information is not sufficient for making a commitment to retrofit the entire series or fleet, then it should be possible to perform a sample retrofit on a small number of railcars. The performance of the sample railcars can be monitored before and after the retrofit. Using the performance measures, the cost

models can then be exercised to determine estimates of maintenance cost savings. These savings can be compared with the retrofit cost to determine whether or not the retrofit will pay off.

5.3.4 Changes in Maintenance Practice

With regard to changes in existing maintenance practice, two courses of action can be taken, as discussed previously. The first alternative is to change the maintenance procedure (increase MTTM) and the second is to change the maintenance interval (decrease MTBI). Section 4 pointed out the three worst offenders for each of three series. In addition, a summary of the subsystem reliability (MTBF) estimates is of interest in view of the related estimates of mean time between inspection (MBTI) detailed in Appendix D. This summary is presented in Exhibit 5-14. The data indicate that for some of the worst offenders the MTBF is less than the MTBI. For example, for the 2200-Series, three subsystems, doors/communication, carbody, and propulsion, can be expected to fail in the time period between inspections. For the 2400-Series there are four such subsystems and for the newer 2600-Series there are two.

In view of the above, it would be prudent to establish the nature of the problem with the identified subsystem so that appropriate adjustments can be made in either the inspection or repair procedures. This can involve documenting (through discussions with repairmen and maintenance supervision) the kinds and extent of repairs that are being required. Then, for some period, say one month, additional repair documentation on maintenance of the subsystem can be required. In addition, intensive investigations of failures and repairs for the subject subsystem can be conducted during the period. This documentation should form a sufficient basis for further action regarding inspection or repair procedures or schedules. Changes in maintenance actions include changes in the frequency of maintenance or changes in maintenance procedures or both.

As an example, consider the 2400-Series propulsion subsystem. At present, scheduled maintenance is performed as part of the routine 6,000-mile inspection for each car. Changes in existing maintenance practice can be accomplished by either changing the scheduled maintenance interval for this particular subsystem or changing the maintenance procedure. Recognizing that it may be impractical to do this on a fleet-wide basis, CTA could conduct a test on a test sample of the 2400-

EXHIBIT 5-14

SUMMARY OF SUBSYSTEM RELIABILITY CALCULATIONS FOR SAMPLE SET BY RAILCAR SERIES

SUBSYSTEM	MEAN TIME BETWEEN FAILURE (HOURS)		
	2200-Series	2400-Series	2600-Series
Doors/Communication	205	275	190
Car Body	216	330	373 (419)*
Propulsion	275 (348)*	216	529
Brakes	356	322 (412)*	479
ATC	446	507	774
HVAC	485	1467	839
Trucks	2017	4414	2516

* Number in parenthesis indicates the calculated value of mean time between inspection for the car series.

Series (say 20 cars) for a period of about 3 months. The scheduled maintenance frequency for the propulsion system of these sample cars could be increased to, say, 4,000-mile intervals. This may help in spotting more incipient failures before they cause service disruption. Then the impact upon railcar performance and cost can be estimated through the cost model. Alternatively, the maintenance frequency could be decreased to 8,000 miles and a performance/cost analyses performed. (The evolution of maintenance intervals of PATCO was discussed in Section 3.4.2.; on a purely trial and error basis it took about 4 years to find the optimum interval.)

Alternatively, more thorough inspection of the propulsion subsystem for these sample cars can be conducted within the current 6,000-mile interval. These changes in maintenance schedules or procedures should be monitored to determine if the performance of the subsystem has been affected. Also, the additional cost (labor and/or material) needed to accomplish such changes in schedules or procedures for maintaining the sample cars should be determined. Suppose it is found that these changes result in 10 percent reduction in total number of maintenance actions experienced by the sample, approximately $400,000 in annual maintenance cost can be saved (see Exhibit 5-4). In addition, this could result in a lower fleet requirement (see Exhibit 5-9). To justify the change in maintenance practice, these potential cost savings can then be compared with the estimated additional cost to effect such changes in maintenance for the entire fleet.

6.0 OTHER CONSIDERATIONS

6.1 CTA MANPOWER AND FACILITIES

The existing CTA maintenance staff is geared toward carrying out the 6,000-mile railcar inspections and undertaking the running repairs and component exchange/rebuild activities necessary to keep the system operating. One reason for the structure and policy of the current preventive maintenance program is the maintenance budget which limits staff size. An expanded preventive maintenance program or an in-house overhaul program would require additional technical staff as well as concomitant employee facilities, training, and management resources. Staffing up for an in-house overhaul effort of the magnitude described in Section 3.6 means that the maintenance and overhaul staffs will be either mixed crews of new and experienced repairmen or separated in some way between maintenance and overhaul activities. In any case, before staffing up for such an effort CTA must also recognize that it will require funding and staff beyond 1994. Analyses with the cost model can be used to determine cost savings potential and, thereby, set the stage for initial funding.

In addition, an in-house overhaul program will require substantial training; the training would involve three separate aspects:

1. Training experienced staff for the overhaul;
2. Training new staff for the overhaul; and
3. Training new staff for preventive maintenance activities.

The actual training requirement will depend, in part, on how new and experienced staff are to be assigned during the initial stages of the overhaul. The need for training experienced staff for the overhaul activities has been verified by the CTA engineering staff.

With regard to existing maintenance facilities, Exhibit 6-1 provides a summary of the characteristics of the CTA facilities together with information on needed or currently planned improvements. It is evident from this list that the only CTA

EXHIBIT 6-1
SUMMARY OF THE CHARACTERISTICS OF THE CTA FACILITIES

FACILITY NAME	FACILITY FUNCTION	PROPOSED AND PLANNED IMPROVEMENTS*
Skokie Maintenance Facility (1927) 160,000 sq. ft.	CTA's major repair shop; provides a complete overhaul and component repair; capability to repair motors and trucks, to perform wheel trueing, body repair, and painting; it contains a degreasing room, foundry, and complete electrical/electronic repair facilities	roof, door, and skylight replacement; provide additional storage areas, a 15-ton crane, a motor repair oven; update the exterior transfer table; new degreasing equipment; four 120-ft. inspection pits; track door air curtains; update the AC power supply
Harlem Inspection Facility (1965) 38,000 sq. ft.	designed and used for running repairs, trouble repairs, and unit changeouts; has four tracks with one being a posted rail track with inspection pit; three remaining tracks have truck and body hoists with one track having turntables for truck removal; an additional structure has been added to serve as blowout area and inspection pit	roof and door replacements; provide new car wash and lighting in blowout area and new blowout systems; provide new 220-volt single phase serevice in shop area and new stinger system
Des Plaines Inspection Shop (1961) 27,360 sq. ft.	designed and used for running repairs, trouble repairs, and unit changeouts; has two through tracks with inspection pits and one stub-end track with truck and body hoist	needs an enclosed extension to accommodate 8-car trains; needs an enclosed car wash and a blowout system
54th Street Inspection Shop (1974) 12,000 sq. ft.	designed and used for running repairs, trouble repairs, and unit changeouts; original shop was scaled down at time of construction due to lack of capital	needs roof replacement; needs addition to achieve original design and to accommodate a 4-car train; needs truck and body hoists
Rosemont Shop (1984) 41,000 sq. ft.	designed and used for running repairs, trouble repairs, and unit changeouts; equipped with a car wash, blowout and collection equipment, a shop area with two tracks with truck and body hoist, turntables, and a stinger system	no major repairs needed
Howard Inspection Shop (1973) 6,300 sq. ft.	used for running repairs, trouble repairs, and unit changeouts for 340 vehicles on the North-South Line	need for larger facility which would necessitate total reorganization of yard space and a totally new facility
Kimball Inspection Shop (1907) 6,600 sq. ft.	an inspection shop which is inadequate for the work performed in an inspection shop; it can accommodate only four vehicles	entire facility needs to be replaced
Wilson Inspection Shop (1902) 39,000 sq. ft.	an inspection shop which is in very poor condition	entire facility needs to be replaced
98th Street Inspection Shop (1969) 35,000 sq. ft.	used for running repairs, trouble repairs, and unit changeouts; can accommodate up to eight vehicles on two tracks with floor jacks and body hoists	needs additional tracks with jacks and body hoists, a blowout collection system, and a larger freight elevator, a new stinger system, and a total shop realignment
61st Street Inspection Shop (1895) 47,000 sq. ft.	basically an inspection shop with seven tracks; no car wash or blowout facility; running repairs must be made without truck and body hoists	entire facility needs to be replaced
Racine Inspection Shop (1975) 9,000 sq. ft.	used for running repairs, trouble repairs, and unit changeouts; has two inspection pits	needs expansion to accommodate two full-length inspection tracts; a truck and body hoist should be added

* Current Condition Report, Chicago Transit Authority Rapid Rail System, Preliminary Report, prepared by Gannett Fleming Transportation Engineers, Inc. for the Urban Mass Transportation Administration, 1984

facility possibly suitable for use in an in-house overhaul program is Skokie shop. However, since it is currently the only CTA facility used for heavy repair, it is preferable to seek an alternative site for any extensive in-house overhaul work.

6.2 CTA PARTS SUPPLY/RECORDS SYSTEM

The primary purpose of examining CTA's parts supply and records system in this study was to determine if the parts records data could be used in assessing the existing maintenance practices. Although simple parts consumption records can be used as a guideline in determining major problem areas with either subsystems/ components or maintenance practices this information must be closely tied to information about maintenance actions before any significant conclusions can be reached. To be of use in assessing maintenance practices, parts records should enable one to link parts usage to individual cars and to individual vehicle failure events. Recent studies of railcar reliability report that most rail transit authorities do not report information of this type; as has been pointed out previously, CTA is no exception to this general rule although once the implementation of its new rail maintenance management information system is complete, it may be possible to correlate vehicle failure events with bench maintenance of components removed from a vehicle and/or parts replacement (Ref. 2).

A second reason for examining the parts supply and records system was the recognition that it must be able to support an in-house overhaul project as well as the continuing maintenance needs of the fleet. The importance of the system stems from a number of requirements, including the following:

1. The need to correlate parts acquisition with parts demand so that an adequate supply of parts is available when needed.

2. The need to avoid an oversupply of parts, which would increase purchase costs (tying up money before it is necessary) and also increase storage and inventory costs.

3. The need to segregate parts supplies for maintenance from those earmarked for overhaul so that both activities can be carried out as scheduled and so that costs can be properly assigned.

4. The desirability of being able to track parts used in the overhaul effort so that any abnormal failure trends in the overhauled equipment can be properly identified and rectified, particularly in view of potential fleet-wide problems.

CTA's parts supply and records system was examined with regard to the above with the following results:

1. Although personnel from a number of groups are involved in parts purchasing, parts stores, and parts usage, there is an existing infrastructure which enables parts and equipment to be stored and delivered as needed. It is reasonable to expect that additional coordination would be required for efficient and effective parts acquisition for an in-house overhaul project if only because additional people will be involved and in view of the importance of work scheduling. There is no reason to believe that it cannot be done at CTA with proper planning.

2. Parts acquisition would have to be carefully planned and even though the terminals do not now have a parts inventory control system, CTA is strongly advised to implement one at the site of an in-house overhaul project.

3. The existing parts acquisition system together with a shop inventory control and storage system should be sufficient to ensure segregation of parts suppliers.

4. Job records for the overhaul should include parts records; the MMIS currently being implemented at CTA should enable engineers to track subsystem failures in such a way that problems with parts related to the overhaul project can be identified and rectified before they become fleet-wide.

REFERENCES

1. Muotoh, D., and C. Elms, Cost Savings Potential From Improvement in Railcar Reliability and Maintainability, UMTA Report UMTA-It-06-0273-84-1, Washington, D.C., April 1984.

2. Task 4 Interim Report from Transit Reliability Information Program (TRIP), "Rapid Rail Transit Vehicle Guidelines for the Operation and Use of the TRIP Data Bank", April 16, 1979, Dynamics Research Corporation, Contract Number DOT-TSC-1559.

APPENDIX A

EQUIPMENT FAILURES, RELIABILITY CONSIDERATIONS, AND DATA AVAILABILITY

For this study we were seeking information about equipment failures, maintenance actions, and inspection activities that would enable us to estimate equipment reliability, etc. From previous studies we were aware that the data which transit properties collect is somewhat similar but that it varies in kind and extent. Some data is generally available on revenue service incidents, periodic inspections, and maintenance activities. The data is generated in the same basic manner at most properties: a vehicle problem is reported in revenue service, or is discovered during preventive maintenance; the vehicle is repaired; and, the information concerning the maintenance action is recorded. It is the range in the depth of detail which is reported and the methodology used by the properties in recording this information which varies considerably.

More specifically, the problems which occur in revenue service are either communicated orally by the train operator to central operations ("central" or "transportation," or the tower having jurisdiction over the particular line) or, with some properties, recorded by the train operator onto a form which is passed on to maintenance. In the case of oral communication, the problem description is retransmitted by central operations to maintenance via telephone or computer terminal, and the information is transcribed onto a maintenance form to initiate a repair activity.*

The suspected revenue service vehicle failure which is initially recorded on an incident report is based on observation and not equipment tear-down and/or repair. Thus, incident reporting of failures is not complete and cannot be used to determine actual equipment reliability without the associated maintenance report describing the repairs undertaken.

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* *Adapted from Transit Reliability Information Program (TRIP), Task 4 Interim Report, "Rapid Rail Transit Vehicle Guidelines for the Operation and Use of the TRIP Data Bank", April 16, 1979, Dynamics Research Corporation, Contract Number DOT-TSC-1559.*

Major differences between transit authorities begin at the reporting of primary repair data, that is, recording what was done to the vehicle and/or its subsystems to complete the repair. Some transit properties, for example, provide only a narrative summary of the repair activity which is also recorded onto the respective incident forms. Other properties provide narrative data to describe each defect found and the repairs made; defective parts or assemblies are identified by part number. Use of a table of fault codes for the mode of failure is sometimes used as is the coding of repair tasks. CTA's new rail MMIS uses a set of repair task codes designed specifically for CTA to be compatible with the digital data input equipment used by the repairman to log on and log off the job.

It is also interesting to note that repair activites involving components removed from a vehicle usually cannot be related to the revenue service incident through the existing data collection methods. Therefore, the reporting of vehicle reliability data stops at whatever the lowest replaceable unit might be for a vehicle subsystem. The structure of some maintenance information systems is such that a link is provided between primary and secondary maintenance data. In general, secondary maintenance (i.e., maintenance performed in the shop on components that have been removed from a railcar) statistics are kept by the properties for the purpose of production control and material and time/cost accounting.

The referenced document reported the following observations and conclusions about transit railcar reliability data:

1. *The total extent of data that would normally be collected to support classical, detailed reliability analysis of transit equipment is not usually collected by the transit authority;*

2. *Only that maintenance data which pertains to what was done to and on the vehicle itself (primary maintenance) can generally be correlated to a vehicle failure;*

3. *Secondary (bench) maintenance of components removed from a vehicle cannot be traced to a vehicle failure event through existing data forms at most transit authorities;*

4. *Failure data is recorded to different levels of equipment detail at different transit authorities.*

Based upon the previous characterization of failure data collected in the rail transit industry, it is important to clarify what is meant by revenue service reliability. The most common measure of hardware reliability is mean time (or distance) between failures (MTBF or MDBF). This measure is not always available because of the data collected by the transit authorities and yet this measure and its companion, mean time to repair (MTTR), can provide the best basis for maintenance management and planning decisions.

Thus, although a transit authority may not collect information in sufficient detail to accurately determine failure cause and effect, it normally does record the fact that, whatever the apparent problem, a correction was made which returned the vehicle to revenue service availability. Data which is collected most often presents the unscheduled maintenance action (repair) which took place and a description of components which were replaced. These data, while not specifically desciptive of railcar or component reliability, will be proportional to hardware reliability values and will describe major contributing factors to the cost of maintenance.

EQUIPMENT RELIABILITY AS IMPACTED BY DESIGN

In some cases, equipment reliability is impacted more by design considerations than by preventive maintenance actions. In other words, no amount of preventive maintenance can improve the reliability of fundamentally unreliable equipment. In this case, complete component changeout is necessary to improve reliability and may also reduce the total amount of time the equipment is held out for repairs.

For example, the Port Authority Transit Corporation, PATCO, purchased 75 cars from the Budd Company to initiate service in 1969. The cars had WABCO N-2 couplers which had a spear with latch design with plastic-housed connectors in the electrical head. The couplers proved to be unreliable to the point that two Equipment Department employees were required to be stationed in the yard during

rush hours to assist the Operations Department in coupling the cars. After reviewing various modifications, it was decided in 1974 to change out the couplers. Once the changeout was complete, Equipment Department (maintenance) man-hours devoted to coupler maintenance dropped from 6% of total to less than 1% of total. Train delays due to failure of trainline door circuits were reduced from several per day to a few per month. No amount of maintenance could have improved the performance of the original couplers.

AGE-RELIABILITY CHARACTERISTICS

At one time it was believed that all equipment would show wearout characteristics and for this reason preventive maintenance and equipment overhaul schedules for rail transit have traditionally been based on wear-related assumptions. The well-known bathtub curve applies to equipment which wears out according to use or time. This age-reliability curve has three identifiable regions:

1. *An infant-mortality region, the period immediately after manufacture or overhaul in which there is a relatively high probability of failure,*

2. *A region of constant and relatively low failure probability, and*

3. *A wearout region, in which the probability of failure begins to increase rapidly with age.*

If the failure pattern of an item does in fact fit this curve, it is reasonable to conclude that the overall failure rate will be reduced if some action is taken just before the item enters the wearout range. In these cases, allowing the item to age well into the wearout region would cause an appreciable increase in the failure rate. Note, however, that such action will not have much effect on the overall rate unless there is a high probability that the item will survive to the age at which wearout appears.

The presence of a well-defined wearout region is not universal although for a large number of mechanical items it is the case. Other possible wearout

patterns exist; for example, a constant or gradually increasing failure probability followed by a pronounced wearout region or a constant probability of failure at all ages. The basic difference between the failure patterns of complex and simple items has important implications for maintenance. Usually the conditional-probability curve for a complex item will show some infant mortality; often the probability of failure right after installation is fairly high. Usually, also, the conditional-probability curves show no marked point of increase with increasing age; the failure probability may increase gradually or remain constant, but there is no age that can be identified as the beginning of a wearout zone. For this reason, unless there is a dominant failure mode, an age limit does little or nothing to improve the overall reliability of a complex item. In fact, scheduled overhaul has been shown to increase the overall failure rate by introducing a high infant-mortality rate in an otherwise stable system.

In contrast, simple items frequently do show a direct relationship between reliability and increasing age. This is particularly true of parts subject to metal fatigue or mechanical wear and items designed as consumables. In this case an age limit based on some maximum operating age or number of stress cycles may be highly effective in improving the overall reliability of an item. Such limits, in fact, play a major role in controlling critical-failure modes since they can be imposed on the part or component in which a given type of failure originates.

It is important to note that although equipment failure rates are important in maintenance programs in making cost decisions and in establishing appropriate intervals for maintenance tasks, they say nothing about which tasks are appropriate or the consequences that dictate their objective. Thus the effectiveness of a particular maintenance solution can be evaluated only in terms of the safety or economic consequences it is intended to prevent. An equipment failure should be evaluated in terms of both its probability of occurrence and the consequences of such a failure.

In the worst case a failure in service can result in a train delay, delays to following trains, and associated passenger delays. In addition, such failures result in lost car-hours, increased maintenance requirements, and consequently,

increased operating and maintenance costs. In practice it is often possible to continue to operate a failed railcar within a train until it completes its run to a line terminal. In some cases such cars cause only reduced service to passengers (doors which must be manually operated or failed air comfort systems) while in others the cars must be locked out of service, decreasing the level of service by reducing line capacity.

LEVEL OF MAINTENANCE AND RELATED COSTS

Preventive maintenance is designed to ensure that equipment remains operational, that the equipment realizes its design life, and that failures in service, and the concomitant costs, are minimized. Most transit authorities establish their own maintenance intervals, based upon the combination of suppliers' recommendations, their own experience, and the experience of others. (The latter is usually a minimal, if any, consideration because of the various differences among transit authorities, i.e., the rolling stock, track condition, maintenance training and capabilities, etc.) The maintenance intervals also reflect the equipment in use, the duty cycle, the skills of the maintenance staff, and the maintenance facilities.

For example, in 1969 PATCO adopted a 6,000-mile interval for inspections. The inspection required 5 persons per car (one electronic technician, two electricians, and two mechanics) for 5 hours. It was soon found that a 6,000-mile interval was too frequent; little repair work was necessary. The interval was increased to 7,500 miles, then 9,000, and finally, in 1972, to 12,000 miles. This was found to be optimum. At times cars would be missed and if allowed to operate up to 15,000 miles they would require extensive work and too many parts. Thus, the 12,000 interval was adopted as an optimum interval.

APPENDIX B

OPERATIONAL DATA REDUCTION

Data reduction needed for the analysis of CTA operations includes an estimation of the number of cars of each series required for service as well as the corresponding car-hours scheduled. Estimates of the number of cars of each series required for service are calculated on the assumption that each series has an equal chance of being picked for service on each route. (Estimates have been adjusted to account for operations of cars as married pairs as appropriate.)

Number of Cars Required for Service

Only those lines on which the 2200-, 2400-, and 2600-series cars operate are considered in estimating railcar requirement for each series. See Exhibit 4-3 for railcar assignment. Therefore, the lines of interest include West-Northwest, West-South, North-South, and Ravenswood.

1. <u>West-Northwest Line</u>

The West-Northwest line includes 2200-, 2600-, and 6000-series.

Total cars assigned = 384

Required for Service = 280

2200-Series

$$\text{Reqd for service} = \frac{144}{384} \times 280 = 105, \text{ say } 106 \text{ cars}$$

2600-Series

$$\text{Reqd for service} = \frac{138}{384} \times 280 = 100 \text{ cars}$$

6000-Series

$$\text{Reqd for service} = \frac{102}{384} \times 280 = 74 \text{ cars}$$

2. <u>West-South Line</u>

The 2000-, 2400-, 2600-series cars operate on this line.

Total cars assigned = 266

Required for Service = 216

2000-Series

$$\text{Reqd for service} = \frac{22}{266} \times 216 = 18 \text{ cars}$$

2400-Series

$$\text{Reqd for service} = \frac{172}{266} \times 216 = 140 \text{ cars}$$

2600-Series

$$\text{Reqd for service} = \frac{72}{266} \times 216 = 58 \text{ cars}$$

3. ***North-South Line***

The 2000-, 2400-, and 6000-series cars are assigned to this line.

Total cars assigned = 330

Required for Service = 224

2000-Series

$$\text{Reqd for service} = \frac{154}{330} \times 224 = 105, \text{ say } 106 \text{ cars}$$

2400-Series

$$\text{Reqd for service} = \frac{22}{330} \times 224 = 15, \text{ say } 16 \text{ cars}$$

6000-Series

$$\text{Reqd for service} = \frac{154}{330} \times 224 = 104 \text{ cars}$$

4. ***Ravenswood Line***

Ravenswood line includes 2600-, and 6000-series cars.

Total cars assigned = 116

Required for Service = 96

2600 Series

$$\text{eqd for service} = \frac{40}{116} \times 96 = 33, \text{ say } 34 \text{ cars}$$

6000-Series

$$\text{Reqd for service} = \frac{76}{116} \times 96 = 63, \text{ say } 64 \text{ cars}$$

Accumulating the above estimates for 2200-, 2400- and 2600-series, the number of cars needed for service are shown in the following table.

Number of Cars Required for Service

Car Series	*W-NW*	*W-S*	*N-S*	*Ravens-wood*	*Total Reqd For Service*	*Fleet Size*	*Current Spare Level*
2200	106	-	-	-	106	144	38
2400	-	140	16	-	156	194	38
2600	100	58	-	34	192	250	58

Estimation of Car-hrs Scheduled

Railcar requirement by period of day is shown in the following table which was obtained from CTA for rush and base periods. The owl requirement is as per CTA data of March 18, 1984.

Equipment Requirement*

Route	*Equipment Required (Cars)*		
	Rush	*Base*	*Owl*
Evanston Express	66	6	0
Evanston Shuttle	-	8	2
North-South	224	104	20
Ravenswood	96	32	0
Skokie Swift	5	2	0
West-Northwest	280	104	12
West-South	224	96	8
	895	352	42

* *Source: Rail System Operating Facts (OP-x83197)*

Car-Hrs Scheduled for 2200-Series Each Weekday

No. Reqd During Rush Period		106
No. Reqd for Base Period	$\frac{352}{895}$ X 106	42
No. Reqd for Owl Period	$\frac{42}{895}$ X 106	5, say 6

Estimated Weekday Car-Hrs

Period	Hours	Cars Scheduled	Car-Hrs Scheduled
6:00 a.m.-8:30 a.m. (Rush)	2.5	106	265
8:30 a.m.-3:30 p.m. (Base)	7.0	42	294
3:30 p.m.-5:30 p.m. (Rush)	2.0	106	212
5:30 p.m.-11:00 p.m. (Base)	5.5	42	231
11:00 p.m.-6:00 a.m. (Owl)	7.0	6	42
			1,044 car-hrs/weekday

Estimated Weekend/Holiday Car-Hrs

Period	Hours	Cars Scheduled	Car-Hrs Scheduled
6:00 a.m.-11:00 p.m. (Base)	17	42	714
11:00 p.m.-6 a.m. (Owl)	7	6	42
			756 car-hrs/day

Assume 250 weekdays, 12 holidays, and 104 weekends

Assume holiday and weekend schedules to be the same -- base + owl

Total Estimated Car-Hrs Scheduled in 1984 (for 2200 Series)

Car-hrs scheduled = (1,044 X 250) + (756 X 116) = 261,000+ 87,696
= 348,696 car-hrs, say 349,000 car-hrs

Car-Hrs Scheduled for 2400-Series Each Weekday

No. Reqd During Rush Period		156
No. Reqd for Base Period	$\frac{352}{895}$ X 156	61, say 62
No. Reqd for Owl Period	$\frac{42}{903}$ X 156	7, say 8

Estimated Weekday Car-Hrs

Period		Hours	Cars Scheduled	Car-Hrs Scheduled
6:00 a.m.-8:30 a.m.	(Rush)	2.5	156	390
8:30 a.m.-3:30 p.m.	(Base)	7.0	62	434
3:30 p.m.-5:30 p.m.	(Rush)	2.0	156	312
5:30 p.m.-11:00 p.m.	(Base)	5.5	62	341
11:00 p.m.-6:00 a.m.	(Owl)	7.0	28	156
				1,533 car-hrs/weekday

Estimated Weekend/Holiday Car-Hrs

Period		Hours	Cars Scheduled	Car-Hrs Scheduled
6:00 a.m.-11:00 p.m.	(Base)	17	62	1,054
11:00 p.m.-6 a.m.	(Owl)	7	28	56
				1,110 car-hrs/day

Total Estimated Car-Hrs Scheduled in 1984 (for 2400-Series)

Car-hrs = (1,533 X 250) + (1,110 X 116) = 383,250 + 128,760
= 512,010 car-hrs, say 512,000 car-hrs

Car-Hrs Scheduled for 2600-Series Each Weekday

No. Reqd During Rush Period		*192*
No. Reqd for Base Period	$\frac{352}{895} \times 192$	*76*
No. Reqd for Owl Period	$\frac{142}{895} \times 192$	*9, say 10*

Estimated Weekday Car-Hrs

Period	*Hours*	*Cars Scheduled*	*Car-Hrs Scheduled*
6:00 a.m.-8:30 a.m. (Rush)	*2.5*	*192*	*480*
8:30 a.m.-3:30 p.m. (Base)	*7.0*	*76*	*532*
3:30 p.m.-5:30 p.m. (Rush)	*2.0*	*192*	*384*
5:30 p.m.-11:00 p.m. (Base)	*5.5*	*76*	*418*
11:00 p.m.-6:00 a.m. (Owl)	*7.0*	*10*	*70*
			1,884 car-hrs/weekday

Estimated Weekend/Holiday Car-Hrs

Period	*Hours*	*Cars Scheduled*	*Car-Hrs Scheduled*
6:00 a.m.-11:00 p.m. (Base)	*17*	*76*	*1,292*
11:00 p.m.-6 a.m. (Owl)	*7*	*10*	*70*
			1,362 car-hrs/day

Total Estimated Car-Hrs Scheduled in 1984 (for 2600-Series)

Car-hrs = (1,884 X 250) + (1,362 X 116) = 491,000 + 157,992
= 628,992 car-hrs, say 629,000 car-hrs

APPENDIX C

FLEET RELIABILITY/MAINTAINABILITY EXTRAPOLATION

Note: The extrapolation of reliability/maintainability for each series assumes that all cars in each fleet are operable and that cars in the fleet are circulated as required.

C.1 2200-SERIES CALCULATIONS

C.1.1 MAINTENANCE ACTIONS

Sample Data Summary for 1984

Fleet size	144 cars
Sample size	10 cars
No. of maint actions, n_m	556
No. of failures, n_f	485
No. of inspections, n_i	71
Repair time, t_r	430 hrs
Inspection time, t_i	284 hrs
Total maint time, t_m	714 hrs

No. of Failures for Fleet

n_f = 485 failures for sample

$N_f = \frac{144}{10} \times 485 = 6{,}984$ failures per year for series

Repair Time

t_r = 430 hrs for sample

$T_r = 14.4 \times 430 = 6{,}192$ hrs for series $= D_s$

No. of Maintenance Actions

n_m = 556 actions for sample

$N_m = 14.4 \times 556 = 8{,}006$ maint. actions per year for series

Total Maintenance Time

t_m = 714 hours for sample

$T_m = 14.4 \times 714 = 10{,}282$ hours per year for series $= D_m$

No. of Inspections

n_i = 71 inspections for sample

N_i = 14.4 X 71 = 1,022 inspections per year for series

Inspection Time

T_i = 1,022 X 4 = 4,088 hrs per year for series

Fleet Mileage

71 inspections for 10 cars translates to an average of 7 inspections per car per year @ approx. 6,000-mile interval, i.e., 42,000 miles per car per year

Fleet Mileage = 42,000 X 144 = 6,048,000 per year

C.1.2 2200-SERIES RELIABILITY/MAINTAINABILITY MEASURES

Mean Time To Repair *(unscheduled maintenance only)*

$$MTTR = \frac{D_s}{N_f} = \frac{6,192}{6,984} = 0.89 \text{ hrs, say } 0.9 \text{ hrs}$$

Mean Time To Maintain *(unscheduled + scheduled)*

$$MTTM = \frac{D_m}{N_m} = \frac{10,282}{8,006} = 1.28 \text{ hrs, say } 1.3 \text{ hrs}$$

Mean Time Between Failure

$$MTBF = \frac{\text{Car-hrs scheduled}}{N_f} = \frac{349,000}{6,984} = 50 \text{ car-hrs per failure}$$

Mean Time Between Maintenance Actions

$$MTBM = \frac{\text{Car-hrs scheduled}}{N_m} = \frac{339,000}{8,006} = 44 \text{ car-hrs per maintenance action}$$

Mean Time To Restore

The ratio of total car downtime to car repair time was found to be approximately equal to 6 for Washington Metropolitan Area Transit Authority. Since data on total car downtime is not available, this ratio is used to obtain mean time to restore for CTA. Applying this ratio to CTA and allowing for married pairs,

R_e = 2 X 6 X 0.9 = 10.8 car-hrs, say 11 car-hrs

Mean Time Between Inspections

$$MTBI = \frac{\text{Car-hrs scheduled}}{N_i} = \frac{344{,}000}{1{,}002} = 348 \text{ car-hrs}$$

Fleet Availability

$$A_v = \frac{MTBM}{MTBM + R_e} = \frac{44}{55} = 0.80 \text{ or } 80 \text{ percent}$$

Estimated Fleet Size

$$\text{Fleet Size} = \frac{\text{Number of cars reqd for service}}{\text{Fleet availability}} = \frac{106}{0.8} = 132.5 \text{ say } 133 \text{ cars}$$

Hence estimated spares = 134 - 106 = 28 cars

C.2 2400-SERIES CALCULATIONS

C.2.1 MAINTENANCE ACTIONS

Sample Data Summary for 1984

Fleet size	194 cars
Sample size	10 cars
No. of maint actions, n_m	540
No. of failures, n_f	476
No. of inspections, n_i	64
Repair time, t_r	330 hrs
Inspection time, t_i	256 hrs
Total maint time, t_m	586 hrs

No. of Failures for Fleet

n_f = 476 failures for sample

$N_f = \frac{194}{10}$ X 476 = 9,234 failures per year for series

Repair Time

t_r = 330 hrs for sample

T_r = 19.4 X 330 = 6,402 hrs for series = D_s

No. of Maintenance Actions

n_m = 540 for sample

N_m = 10,476 maintenance actions per year for series

Total Maintenance Time

t_m = 586 hrs

T_m = 11,368 hrs per year for series = D_m

No. of Inspections

n_i = 64

N_i = 1,242 inspections per year for series

Inspection Time

T_i = 1,242 X 4 = 4,968 hrs per year for series

Fleet Mileage

6.4 inspections per car per year
@ 6,000-mile interval, or
38,400 miles per car per year

Fleet Mileage = 7,449,600 per year, say 7,450,000 per year

C.2.2 2400-SERIES RELIABILITY/MAINTAINABILITY MEASURES

Mean Time To Repair (unscheduled maintenance only)

$$MTTR = \frac{D_s}{N_f} = \frac{6,402}{9,234} = 0.69 \text{ hrs or } 0.7 \text{ hrs}$$

Mean Time To Maintain (unscheduled + scheduled)

$$MTTM = \frac{D_m}{N_m} = \frac{11,368}{10,476} = 1.1 \text{ hrs}$$

Mean Time Between Failure

$$MTBF = \frac{\text{car-hrs sch.}}{N_f} = \frac{512,000}{9,234} = 55.4 \text{ car-hrs per failure, say } 55 \text{ car-hrs}$$

Mean Time Between Maintenance Actions

$$MTBM = \frac{512,000}{10,476} = 48.9 \text{ car-hrs, say } 49 \text{ car-hrs}$$

Mean Time To Restore

$$R_e = K_{CTA} MTTR = 2 \times 6 \times 0.7 = 8.4 \text{ car-hrs, say } 8 \text{ car-hrs}$$

Mean Time Between Inspections

$$MTBI = \frac{512,000}{1,242} = 412 \text{ car-hrs}$$

Fleet Availability

$$A_v = \frac{49}{59} = 0.86 \text{ or } 86 \text{ percent}$$

Estimated Fleet Size

$$\text{Fleet Size} = \frac{156}{0.86} = 181.4, \text{ say } 182 \text{ cars}$$

Hence estimated spares = 182 - 156 = 26 cars

C.3 2600-SERIES CALCULATIONS

C.3.1 MAINTENANCE ACTIONS

Sample Data Summary for 1984

Fleet size	250 cars
Sample size	8 cars
No. of maint actions, n_m	323
No. of failures, n_f	275
No. of inspections, n_i	48
Repair time, t_r	182 hrs
Inspection time, t_i	192 hrs
Total maint time, t_m	374 hrs

No. of Failures for Fleet

N_f = 275 failures for sample

$N_f = \frac{250}{8}$ X 275 = 31.25 X 275 = 8,594 failures per year for series

Repair Time

t_r = 182 hrs for sample

T_r = 31.25 X 182 [illegible] hrs for series = D_s

No. of Maintenance Actions

n_m = 323 hrs for sample

N_m = 31.25 X 323 = 10,094 maintenance actions per year for series

Total Maintenance Time

t_m = 374 hrs

T_m = 31.25 X 374 = 11,688 hrs per year for series = D_m

No. of Inspections

n_i = 48 inspections for sample

N_i = 31.25 X 48 = 1,500 inspections per year for series

Inspection Time

T_i = 1,500 X 4 = 6,000 hrs per year for series

Fleet Mileage

48 Inspections for eight cars translate to an average of 6 inspections per car per year @ 6,000-mile interval, i.e., 36,000 miles per car per year

Fleet Mileage = 36,000 X 250 = 9 X 10^6 per year

C.3.2 2600-SERIES RELIABILITY/MAINTAINABILITY MEASURES

Mean Time To Repair (unscheduled maintenance only)

$$MTTR = \frac{D_f}{N_f} = \frac{5,688}{8,594} = 0.66 \text{ hrs or } 0.7 \text{ hrs}$$

Mean Time To Maintain (unscheduled + scheduled)

$$MTTM = \frac{D_m}{N_m} = \frac{11,688}{10,094} = 1.16 \text{ hrs, say } 1.2 \text{ hrs}$$

Mean Time Between Failure

$$MTBF = \frac{\text{car-hrs sch.}}{N_f} = \frac{629,000}{8,594} = 73.1 \text{ car-hrs, say } 73 \text{ car-hrs}$$

Mean Time Between Maintenance Actions

$$MTBM = \frac{629,000}{10,094} = 62 \text{ car-hrs}$$

Mean Time To Restore

$$R_e = K_{CTA} MTTR = 2 \times 6 \times 0.7 = 8.4 \text{ car-hrs, say } 8 \text{ car-hrs}$$

Mean Time Between Inspections

$$MTBI = \frac{629,000}{1,500} = 419 \text{ car-hrs}$$

Fleet Availability

$$A_v = \frac{62}{70} = 0.885 \text{ or } 89 \text{ percent}$$

Estimated Fleet Size

$$\text{Fleet size} = \frac{192}{0.89} = 216 \text{ cars}$$

$$\text{Hence estimated spares} = 216 - 192 = 24 \text{ cars}$$

APPENDIX D

SUBSYSTEM RELIABILITY/MAINTAINABILITY EXTRAPOLATION

D.1 2200-SERIES SAMPLE*

Failures or Unscheduled Maintenance Actions (UMA)

Doors/Communications	24% of total failures
Car Body	22%
Propulsion	18%
Brakes	14%
HVAC	10%
ATC	10%
Trucks	2%

Repair Time

Propulsion	37% of total repair time
Doors/Communication	19%
Brakes	13%
Car Body	13%
ATC	8%
HVAC	7%
Trucks	3%

* Based on the compilation of data for 5 cars for one year.

SUBSYSTEM MTBF FOR 2200 SERIES

Propulsion

$$n_{fp} = 44 \text{ UMAs for sample}$$

$$N_{fp} = \frac{144}{5} \times 44 = 1{,}267 \text{ UMAs/yr for series}$$

$$H_s = 349{,}000 \text{ car-hrs for series}$$

$$MTBF = \frac{349{,}000}{1{,}267} = 275 \text{ car-hrs/UMA}$$

Car Body

$$n_{fs} = 56 \text{ UMAs for sample}$$

$$N_{fs} = 28.8 \times 56 = 1{,}613 \text{ UMAs/yr for series}$$

$$MTBF = \frac{349{,}000}{1{,}613} = 216 \text{ car-hrs/UMA}$$

Brakes

$$n_{fb} = 34 \text{ UMAs for sample}$$

$$N_{fb} = 28.8 \times 34 = 979 \text{ UMAs/yr for series}$$

$$MTBF = 356 \text{ car-hrs/UMA}$$

Doors/Communications

$$n_{fd} = 59 \text{ UMAs for sample}$$

$$N_{fd} = 28.8 \times 59 = 1{,}699 \text{ UMAs/yr for series}$$

$$MTBF = 205 \text{ car-hrs/UMA}$$

HVAC

$$n_{fh} = 25 \text{ UMAs for sample}$$

$$N_{fh} = 28.8 \times 25 = 720 \text{ UMAs/yr for series}$$

$$MTBF = 485 \text{ car-hrs/UMA}$$

Trucks

n_{ft} = 6 UMAs for sample

N_{ft} = 28.8 X 6 = 173 UMAs/yr for series

MTBF = 2,017 car-hrs/UMA

ATC

n_{fa} = 26 UMAs for sample

N_{fa} = 28.8 X 26 = 749 UMAs/yr for series

MTBF = 466 car-hrs/UMA

SUMMARY SUBSYSTEM MTBF AND MTTR FOR 2200-SERIES

$$MTBF\ (\text{car-hrs/UMA}) = \frac{\text{car-hrs scheduled}}{N_f}$$

Doors/Communication	205
Car Body	216
Propulsion	275
Brakes	356
ATC	466
HVAC	485
Trucks	2,017

$$MTTR\ (\text{hrs}) = \frac{\text{repair time}}{n_f}$$

Propulsion	1.9
Trucks	1.2
Brakes	0.8
ATC	0.8
Doors/Communication	0.7
HVAC	0.6
Car Body	0.5

D.2 2400-SERIES SAMPLE*

Failures or Unscheduled Maintenance Actions (UMA)

Propulsion	27% of all failures
Doors/Communication	21%
Brakes	18%
Car Body	18%
ATC	11%
HVAC	4%
Trucks	1%

Repair Time

Propulsion	28% of total repair time
Brakes	21%
Doors/Communication	15%
Car Body	15%
ATC	13%
HVAC	4%
Trucks	4%

* Based on the compilation of data for 5 cars for one year.

SUBSYSTEM MTBF FOR 2400 SERIES

Propulsion

n_{fp} = 61 UMAs for sample

$N_{fp} = \frac{194}{5} \times 61 = 38.8 \times 61 = 2{,}367$ UMAs/yr for series

H_s = 512,000 car-hrs/yr for series

$MTBF = \frac{512{,}000}{2{,}367} = 216$ car-hrs/UMA

Car Body

n_{fs} = 40 UMAs for sample

N_{fs} = 1,552 UMAs/yr for series

$MTBF = \frac{512{,}000}{1{,}552} = 330$ car-hrs/UMA

Brakes

n_{fb} = 41 UMAs for sample

N_{fb} = 1,591 UMAs/yr for series

$MTBF = \frac{512{,}000}{1{,}591} = 322$ car-hrs/UMA

Doors/Communications

n_{fd} = 48 UMAs for sample

N_{fd} = 1,862 UMAs/yr for series

$MTBF = \frac{512{,}000}{1{,}862} = 275$ car-hrs/UMA

HVAC

n_{fh} = 9 UMAs for sample

N_{fh} = 349 UMAs/yr for series

$MTBF = \frac{512{,}000}{349} = 1{,}467$ car-hrs/UMA

Trucks

n_{ft} = 3 UMAs for sample

N_{ft} = 116 UMAs/yr for series

$$MTBF = \frac{512,000}{116} = 4,414 \text{ car-hrs/UMA}$$

ATC

n_{fa} = 26 UMAs for sample

N_{fa} = 1,009 UMAs/yr for series

$$MTBF = \frac{512,000}{1,009} = 507 \text{ car-hrs/UMA}$$

SUMMARY SUBSYSTEM MTBF AND MTTR FOR 2400-SERIES

$$MTBF\ (car\text{-}hrs/UMA) = \frac{car\text{-}hrs\ scheduled}{N_f}$$

Propulsion	216
Doors/Communication	275
Brakes	322
Car Body	330
ATC	507
HVAC	1,467
Trucks	4,414

MTTR (hrs)

Trucks	1.0
Brakes	0.8
Propulsion	0.7
HVAC	0.7
ATC	0.7
Car Body	0.6
Doors/Communication	0.5

*D.3 2600-SERIES SAMPLE**

Failures or Unscheduled Maintenance Actions (UMA)

Doors/Communication	*36% of total failures*
Car Body	*18%*
Brakes	*14%*
Propulsion	*12%*
ATC	*9%*
HVAC	*8%*
Trucks	*3%*

Repair Time

Doors/Communication	*28% of total repair time*
Brakes	*22%*
Car Body	*20%*
ATC	*11%*
Propulsion	*10%*
HVAC	*7%*
Trucks	*2%*

* *Based on the compilation of data for 4 cars for one year.*

SUBSYSTEM MTBF FOR 2600 SERIES

Propulsion

n_{fp} = 17 UMAs for sample

$N_{fp} = \frac{250}{4} \times 17 = 62.5 \times 17 = 1{,}063$ UMAs/yr for series

H_s = 629,000 car-hrs/yr for series

$MTBF = \frac{629{,}000}{1{,}063} = 592$ car-hrs/UMA

Car Body

n_{fs} = 27 UMAs for sample

$n_{fs} = 62.5 \times 27 = 1{,}688$ UMAs/yr for series

$MTBF = \frac{629{,}000}{1{,}688} = 373$ car-hrs/UMA

Brakes

n_{fb} = 21 UMAs for sample

N_{fb} = 1,313 UMAs/yr for series

$MTBF = \frac{629{,}000}{1{,}313} = 479$ car-hrs/UMA

Doors/Communications

n_{fd} = 53 UMAs for sample

N_{fd} = 3,313 UMAs/yr for series

$MTBF = \frac{629{,}000}{3{,}313} = 190$ car-hrs/UMA

HVAC

n_{fh} = 12 UMAs for sample

N_{fh} = 750 UMAs/yr for series

$MTBF = \frac{629{,}000}{750} = 839$ car-hrs/UMA

Trucks

n_{ft} = 4 UMAs for sample

N_{ft} = 250 UMAs/yr for series

$$MTBF = \frac{629{,}000}{250} = 2{,}516 \text{ car-hrs/UMA}$$

ATC

n_{fa} = 13 UMAs for sample

N_{fa} = 813 UMAs/yr for series

$$MTBF = \frac{629{,}000}{813} = 774 \text{ car-hrs/UMA}$$

SUMMARY SUBSYSTEM MTBF AND MTTR FOR 2600-SERIES

$$\text{MTBF (car-hrs/UMA)} = \frac{\text{car-hrs scheduled}}{N_f}$$

Doors/Communication	190
Car Body	373
Propulsion	592
Brakes	479
ATC	774
HVAC	839
Trucks	2,516

MTTR (hrs)

Brakes	1.0
ATC	0.8
Car Body	0.7
Propulsion	0.6
Trucks	0.6
Doors/Communication	0.5
HVAC	0.5

APPENDIX E

CALIBRATION OF MODELS

This appendix presents the procedure used to calibrate both the maintenance and fleet capital cost savings models. The results obtained from this calibration are applicable only to CTA and are not transferable to other transit systems.

E.1 DATA USED FOR CALIBRATION

The tool used to estimate potential cost savings at CTA is a perturbation model which is calibrated on the basis of results of data reduction efforts discussed in Section 4.3 and Appendices B through D. Various assumptions and estimates were made in this data reduction process. A discussion of these assumptions and estimates are contained in the relevant sections of the report. These assumptions were necessary because of the absence of a comprehensive data base at CTA and also as a means to simplify the required calculations.

It is, therefore, important to reiterate that the level of accuracy of results of these models depends on the validity of these assumptions and estimates. Also, because it is a perturbation model, estimated results will be less accurate for large changes in reliability and maintainability. Such inaccuracies would lead to an overestimation of potential cost savings. However, if the tool underestimated potential cost savings, it might fail to identify benefits from railcar performance improvement. Therefore, for large changes in reliability and maintainability, the tool is conservative in that it will identify cost savings potential and provide the necessary justification for a more detailed investigation.

E.2 CALIBRATION PROCEDURES

Detailed calibration of both maintenance and fleet capital cost savings follows. Results of the sensitivity analysis using the calibrated equations are contained in the following sections.

E.2.1 Maintenance Cost Savings Model

The maintenance cost savings model is given by

$$\Delta C_m = C_{ml}\left\{\frac{p_m + p_t}{1 + p_m}\right\} + C_{mp}\left\{\frac{p_m}{1 + p_m}\right\}$$

2200-Series

Calibrating constants for this series include the following:

Maintenance Labor Cost $= C_{ml} = \$1,104,098$

Spare Parts Cost $= C_{mp} = \$1,730,059$

Substituting in above equation, potential maintenance cost savings for the 2200-Series becomes

$$\Delta C_m = 1,100,000\left\{\frac{p_m + p_t}{1 + p_m}\right\} + 1,700,000\left\{\frac{p_m}{1 + p_m}\right\}$$

2400-Series

Maintenance Labor Cost $= C_{ml} = \$1,867,616$

Spare Parts Cost $= C_{mp} = \$2,037,279$

Resulting potential maintenance cost savings for the 2400-series is given by

$$\Delta C_m = 1,900,000\left\{\frac{p_m + p_t}{1 + p_m}\right\} + 2,000,000\left\{\frac{p_m}{1 + p_m}\right\}$$

2600-Series

Maintenance Labor Cost $= C_{ml} = \$2,170,487$

Spare Parts Cost $= C_{mp} = \$1,079,567$

Resulting potential maintenance cost savings for the 2600-series is given by

$$\Delta C_m = 2,200,000\left\{\frac{p_m + p_t}{1 + p_m}\right\} + 1,100,000\left\{\frac{p_m}{1 + p_m}\right\}$$

B.2.2 Fleet Capital Cost Savings Model

Fleet capital cost savings have been expressed in the form of number of cars that can be saved. The resulting expression is

$$\Delta N_c = N_o\left\{\frac{p_m + p_t}{1 + p_m}\right\}\frac{R_e}{L}$$

2200-Series

Number of cars needed for service = N_o = 106

Mean time to restore = R_e = 11 hours

Mean time between maintenance = L = 44 hours

$$N_c = 106 \left\{\frac{p_m + p_t}{1 + p_m}\right\} \left[\frac{11}{44}\right] = 28 \left\{\frac{p_m + p_t}{1 + p_m}\right\}$$

2400-Series

Number of cars needed for service = N_o = 155

Mean time to restore = R_e = 8 hours

Mean time between maintenance = L = 49 hours

$$N_c = 156 \left\{\frac{p_m + p_t}{1 + p_m}\right\} \left[\frac{8}{49}\right] = 26 \left\{\frac{p_m + p_t}{1 + p_m}\right\}$$

2600-Series

Number of cars needed for service = N_o = 192

Mean time to restore = R_e = 8 hours

Mean time between maintenance = L = 62 hours

$$N_c = 192 \left\{\frac{p_m + p_t}{1 + p_m}\right\} \left[\frac{8}{62}\right] = 24 \left\{\frac{p_m + p_t}{1 + p_m}\right\}$$

E.3 UNIT COSTS

Unit maintenance cost factors from the model development (Ref 1) are estimated as follows. These factors provide a useful insight into the cost-effectivenss of current maintenance practice for each car series.

E.3.1 Maintenance Labor Cost Factor

This factor relates labor cost for scheduled and unscheduled maintenance to total time cars are actually worked on. It represents the labor cost per car-hour of maintenance and is given by

$$K_m = \frac{C_{ml}}{D_m}$$

For the 2200-Series,

$$K_m = \frac{\$1,100,000}{10,282 \text{ car-hrs}} = \$107 \text{ per car-hr}$$

For the 2400-Series,

$$K_m = \frac{\$1,900,000}{11,368 \text{ car-hrs}} = \$167 \text{ per car-hr}$$

For the 2600-Series,

$$K_m = \frac{\$2,200,000}{11,688 \text{ car-hrs}} = \$188 \text{ per car-hr}$$

E.3.2 Spare Parts Cost Factor

This relates spare parts cost for scheduled and unscheduled maintenance to number of maintenance actions experienced during the period under investigation. It represents the average parts cost per maintenance action and is given by

$$K_p = \frac{C_{mp}}{N_m}$$

For the 2200-Series,

$$K_p = \frac{\$1,700,000}{8,006} = \$212 \text{ per maintenance action}$$

For the 2400-Series,

$$K_p = \frac{\$2,000,000}{10,476} = \$191 \text{ per maintenance action}$$

For the 2600-Series,

$$K_p = \frac{\$1,100,000}{10,094} = \$109 \text{ per maintenance action}$$

EXHIBIT E-1

ANNUAL MAINTENANCE COST SAVINGS FOR IMPROVEMENTS IN 2200-SERI
RELIABILITY AND MAINTAINABILITY (FIXED MTBM)

Pm	0	20	40	60	80	100
Pt						
0	0	466667	800000	1050000	1244444	1400000
10	110000	558333	878571	1118750	1305556	1455000
20	220000	650000	957143	1187500	1366667	1510000
30	330000	741667	1035714	1256250	1427778	1565000
40	440000	833333	1114286	1325000	1488889	1620000
50	550000	925000	1192857	1393750	1550000	1675000
60	660000	1016667	1271429	1462500	1611111	1730000
70	770000	1108333	1350000	1531250	1672222	1785000
80	880000	1200000	1428571	1600000	1733333	1840000
90	990000	1291667	1507143	1668750	1794444	1895000
100	1100000	1383333	1585714	1737500	1855556	1950000

EXHIBIT E-2

ANNUAL MAINTENANCE COST SAVINGS FOR IMPROVEMENTS IN 2200-SERI
RELIABILITY AND MAINTAINABILITY (FIXED MTTM)

Pt	0	20	40	60	80	100
Pm						
0	0	220000	440000	660000	880000	1100000
10	254545	454545	654545	854545	1054545	1254545
20	466667	650000	833333	1016667	1200000	1383333
30	646154	815385	984615	1153846	1323077	1492308
40	800000	957143	1114286	1271429	1428571	1585714
50	933333	1080000	1226667	1373333	1520000	1666667
60	1050000	1187500	1325000	1462500	1600000	1737500
70	1152941	1282353	1411765	1541176	1670588	1800000
80	1244444	1366667	1488889	1611111	1733333	1855556
90	1326316	1442105	1557895	1673684	1789474	1905263
100	1400000	1510000	1620000	1730000	1840000	1950000

EXHIBIT E-3

ANNUAL MAINTENANCE COST SAVINGS FOR IMPROVEMENTS IN 2400-SERI
RELIABILITY AND MAINTAINABILITY (FIXED MTBM)

Pm	0	20	40	60	80	100
Pt						
0	0	650000	1114286	1462500	1733333	1950000
10	190000	808333	1250000	1581250	1838889	2045000
20	380000	966667	1385714	1700000	1944444	2140000
30	570000	1125000	1521429	1818750	2050000	2235000
40	760000	1283333	1657143	1937500	2155556	2330000
50	950000	1441667	1792857	2056250	2261111	2425000
60	1140000	1600000	1928571	2175000	2366667	2520000
70	1330000	1758333	2064286	2293750	2472222	2615000
80	1520000	1916667	2200000	2412500	2577778	2710000
90	1710000	2075000	2335714	2531250	2683333	2805000
100	1900000	2233333	2471429	2650000	2788889	2900000

EXHIBIT E-4

ANNUAL MAINTENANCE COST SAVINGS FOR IMPROVEMENTS IN 2400-SERI
RELIABILITY AND MAINTAINABILITY (FIXED MTTM)

Pt	0	20	40	60	80	100
Pm						
0	0	380000	760000	1140000	1520000	1900000
10	354545	700000	1045455	1390909	1736364	2081818
20	650000	966667	1283333	1600000	1916667	2233333
30	900000	1192308	1484615	1776923	2069231	2361538
40	1114286	1385714	1657143	1928571	2200000	2471429
50	1300000	1553333	1806667	2060000	2313333	2566667
60	1462500	1700000	1937500	2175000	2412500	2650000
70	1605882	1829412	2052941	2276471	2500000	2723529
80	1733333	1944444	2155556	2366667	2577778	2788889
90	1847368	2047368	2247368	2447368	2647368	2847368
100	1950000	2140000	2330000	2520000	2710000	2900000

EXHIBIT E-5

ANNUAL MAINTENANCE COST SAVINGS FOR IMPROVEMENTS IN 2600-SERI
RELIABILITY AND MAINTAINABILITY (FIXED MTBM)

Pt \ Pm	0	20	40	60	80	100
0	0	550000	942857	1237500	1466667	1650000
10	220000	733333	1100000	1375000	1588889	1760000
20	440000	916667	1257143	1512500	1711111	1870000
30	660000	1100000	1414286	1650000	1833333	1980000
40	880000	1283333	1571429	1787500	1955556	2090000
50	1100000	1466667	1728571	1925000	2077778	2200000
60	1320000	1650000	1885714	2062500	2200000	2310000
70	1540000	1833333	2042857	2200000	2322222	2420000
80	1760000	2016667	2200000	2337500	2444444	2530000
90	1980000	2200000	2357143	2475000	2566667	2640000
100	2200000	2383333	2514286	2612500	2688889	2750000

EXHIBIT E-6

ANNUAL MAINTENANCE COST SAVINGS FOR IMPROVEMENTS IN 2600-SERI
RELIABILITY AND MAINTAINABILITY (FIXED MTTM)

Pm \ Pt	0	20	40	60	80	100
0	0	440000	880000	1320000	1760000	2200000
10	300000	700000	1100000	1500000	1900000	2300000
20	550000	916667	1283333	1650000	2016667	2383333
30	761538	1100000	1438462	1776923	2115385	2453846
40	942857	1257143	1571429	1885714	2200000	2514286
50	1100000	1393333	1686667	1980000	2273333	2566667
60	1237500	1512500	1787500	2062500	2337500	2612500
70	1358824	1617647	1876471	2135294	2394118	2652941
80	1466667	1711111	1955556	2200000	2444444	2688889
90	1563158	1794737	2026316	2257895	2489474	2721053
100	1650000	1870000	2090000	2310000	2530000	2750000

EXHIBIT E-7

CAPITAL COST SAVINGS FOR IMPROVEMENTS IN 2200-SERIES
RELIABILITY AND MAINTAINABILITY (FIXED MTBM)
(In terms of active fleet reduction)

Pm	0	20	40	60	80	100
Pt						
0	0	5	8	11	12	14
10	3	7	10	12	14	15
20	6	9	12	14	16	17
30	8	12	14	16	17	18
40	11	14	16	18	19	20
50	14	16	18	19	20	21
60	17	19	20	21	22	22
70	20	21	22	23	23	24
80	22	23	24	25	25	25
90	25	26	26	26	26	27
100	28	28	28	28	28	28

EXHIBIT E-8

CAPITAL COST SAVINGS FOR IMPROVEMENTS IN 2200-SERIES
RELIABILITY AND MAINTAINABILITY (FIXED MTTM)
(In terms of active fleet reduction)

Pt	0	20	40	60	80	100
Pm						
0	0	6	11	17	22	28
10	3	8	13	18	23	28
20	5	9	14	19	23	28
30	6	11	15	19	24	28
40	8	12	16	20	24	28
50	9	13	17	21	24	28
60	11	14	18	21	25	28
70	12	15	18	21	25	28
80	12	16	19	22	25	28
90	13	16	19	22	25	28
100	14	17	20	22	25	28

EXHIBIT E-9

CAPITAL COST SAVINGS FOR IMPROVEMENTS IN 2400-SERIES RELIABILITY AND MAINTAINABILITY (FIXED MTBM)
(In terms of active fleet reduction)

Pm	0	20	40	60	80	100
Pt						
0	0	4	7	10	12	13
10	3	7	9	11	13	14
20	5	9	11	13	14	16
30	8	11	13	15	16	17
40	10	13	15	16	17	18
50	13	15	17	18	19	20
60	16	17	19	20	20	21
70	18	20	20	21	22	22
80	21	22	22	23	23	23
90	23	24	24	24	25	25
100	26	26	26	26	26	26

EXHIBIT E-10

CAPITAL COST SAVINGS FOR IMPROVEMENTS IN 2400-SERIES RELIABILITY AND MAINTAINABILITY (FIXED MTTM)
(In terms of active fleet reduction)

Pt	0	20	40	60	80	100
Pm						
0	0	5	10	16	21	26
10	2	7	12	17	21	26
20	4	9	13	17	22	26
30	6	10	14	18	22	26
40	7	11	15	19	22	26
50	9	12	16	19	23	26
60	10	13	16	20	23	26
70	11	14	17	20	23	26
80	12	14	17	20	23	26
90	12	15	18	21	23	26
100	13	16	18	21	23	26

EXHIBIT E-11

CAPITAL COST SAVINGS FOR IMPROVEMENTS IN 2600-SERIES RELIABILITY AND MAINTAINABILITY (FIXED MTBM)
(In terms of active fleet reduction)

Pm	0	20	40	60	80	100
Pt						
0	0	4	7	9	11	12
10	2	6	9	11	12	13
20	5	8	10	12	13	14
30	7	10	12	14	15	16
40	10	12	14	15	16	17
50	12	14	15	17	17	18
60	14	16	17	18	19	19
70	17	18	19	20	20	20
80	19	20	21	21	21	22
90	22	22	22	23	23	23
100	24	24	24	24	24	24

EXHIBIT E-12

CAPITAL COST SAVINGS FOR IMPROVEMENTS IN 2600-SERIES RELIABILITY AND MAINTAINABILITY (FIXED MTTM)
(In terms of active fleet reduction)

Pt	0	20	40	60	80	100
Pm						
0	0	5	10	14	19	24
10	2	7	11	15	20	24
20	4	8	12	16	20	24
30	6	9	13	17	20	24
40	7	10	14	17	21	24
50	8	11	14	18	21	24
60	9	12	15	18	21	24
70	10	13	16	18	21	24
80	11	13	16	19	21	24
90	11	14	16	19	21	24
100	12	14	17	19	22	24